Assessment of Vehicle Fires in New Zealand Parking Buildings

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"There's nothing in the manual about 'smoke,' But hold on, I'm looking up 'fire.'"

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Abstract

This report examines the characteristics of historical data for vehicle fires in New Zealand parking buildings from 1995 to 2003, evaluates the probabilities of such fires using event tree analysis, and presents a cost-benefit analysis model for the provision of sprinklers in parking buildings. The historical data are filtered from New Zealand Fire Service FIRS data and provide the relevant probabilities for the event tree model which considers the type of parking buildings and different vehicle fire spread scenarios. The results from event tree model are applied into cost-benefit analysis model, where the cost-benefit ratio measure is used and annual cost avoidance of vehicle fire damage by sprinklers in the parking building is identified as the benefit. A case study is finally performed for a public parking building with a total floor area of 30,000 m^2 using Monte-Carlo simulation in the @RISK programme.

It is found that on average, there were 12 vehicle fire incidents each year in New Zealand parking buildings. Multiple vehicle fire incidents accounted for approximately 3% of such fires. Deliberately lit is found to be the leading cause of vehicle fires in New Zealand parking buildings (26.7% of all fires). It is concluded that annual vehicle fire frequencies in New Zealand parking buildings are generally lower than those in buildings of other occupancies, and an economically automatic sprinkler system does not justify itself in a parking building situation from the building owner's point of view, based on available data collected during this research. This appears to conform to the requirements for sprinklers placed by the acceptable solution in New Zealand Building Code. Annual usage ratio is found to be the most critical factor in determining the cost-benefit ratio, according to the sensitivity analysis in the case study.

When an automatic sprinkler system is not provided in a closed parking building, it is recommended to have an effective smoke control system to provide tenable conditions for occupants and fire-fighters in the event of a fire; this is also mandatory in the prescriptive acceptable solution in New Zealand Building Code.

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Chapter 1 Introduction

1.1 Initiative for Research

There are thousands of vehicle fires occurring each year in New Zealand. These fires cause the loss of property and pose a hazard to life safety. The combustible materials in a vehicle can include fuel, vehicle upholstery, insulating materials and plastic or trim. The ignition sources in a vehicle may stem from electrical malfunction, sparks generated from engine ignition or friction, hot exhaust components, overheating of mechanical components, engine backfire, careless use of smoking materials and deliberate behaviour.

There has recently been some interest and discussion about vehicle fires, particularly those fires in parking buildings, emanating from the international fire safety engineering community within the news groups on the internet (M. Spearpoint, *pers. Comm.*). The main points of these discussions can be summarised as follows:

- What is the likelihood of vehicle fires in parking buildings, and does the likelihood vary with the type of parking building (eg. private or public)?
- How likely does the fire spread to neighbouring vehicles, and why?
- What are the causes of vehicle fires in parking buildings (eg. arson, ignition, etc.)?
- What materials are involved in vehicle fires in parking buildings?
- What is the severity of the vehicle fires in parking buildings?
- How appropriate is the installation of sprinklers in parking buildings to protect the life safety and/or property?

When assessing fire safety in a parking building, one would first determine the likely frequency of vehicle fires in such buildings. This is also the subject normally brought up first in the vehicle fire discussions. This depends on a number of factors which may include the type of building, and vehicle occupancy during a certain time period etc. The likely frequency of fire in a business car park where vehicles remain for the whole day should be lower than a public facility where vehicle occupancy may be alternating with greater frequency.

The spread of fire between vehicles in a parking building is another topic receiving attention. The radiation effect of fire from the vehicle ignited first is generally considered as the major cause of fire spread; it can cause the ignition of combustible materials on adjacent vehicles such as tyres, windows joint, etc. The fire spread between parked vehicles is dependant on the geometry of the building. In a closed parking building, the compartment effect of burning can increase the likelihood of fire spread. If the fire occurs in a vehicle parked in a parking building open to air, the direction and velocity of wind can influence the fire development significantly. Although there is always the potential of fire spread between parked vehicles for any ventilation condition, the quick intervention of fire-fighters or the operation of sprinklers can prevent this from happening.

The severity of vehicle fires is also a subject of interest, fundamental to fire engineering design for life safety and property protection in parking buildings. Vehicle fire severity involves heat release rate and toxic product concentrations generated by burning vehicles.

The provision of a sprinkler system in a parking building is a topic also attracting specific discussion. There are two groups of thought. One considers the frequency of the fire as low and/or cast doubt on the effect of the sprinklers controlling the fire spread. The other proposes that the sprinklers can control the fire development, providing a tenable condition for the building occupants and fire-fighters, and giving protection for the property.

This report attempts to answer these questions as best as possible using appropriate literature and put these in a New Zealand perspective using relevant New Zealand data. Before the objectives of this research are presented, the introductions are given for the following: parking building definition, case studies of vehicle fires in parking buildings, active fire protection systems in parking buildings, and code requirements of fire safety in parking buildings.

1.2 Parking Buildings

Parking buildings are generally used for the parking of motor vehicles, and do not include private garages and vehicle repairers etc. A parking building can be either private or public type. The private type is generally for people specifically entitled to park there, whereas the public type is for the use of any member of the public. The parking building can be either single level or multi-storied structure, as a standalone building or a structure adjacent to or above/below other occupancy. The structure of a parking building can also be classified to open and closed type, according to the ventilation condition. Building codes usually give the definition of openness of a parking building. Steel and concrete are the most commonly used materials for the parking building construction. The fire safety requirements, including structure fire ratings and provision of fire protection system such as sprinklers, vary between different building codes.

For a parking building, the average floor area per one parking space in this building is defined as the Efficiency (Chrest et al., 2000). As of 2000, the goal of most parking building designs in the US was to achieve an Efficiency of 28 to 30 m^2/space (300 to 325 ft^2/space). The number of parking spaces in a parking building can therefore be expressed by dividing the total floor area by Efficiency. An Efficiency value of 29m^2/space was used for analysis of the parking building in this research.

1.3 Historical Case Studies

Six case studies of vehicle fires in car parks, three in Europe and three in Australia, are introduced in this section. All these vehicle fire incidents, except for the one in the UK, occurred in enclosed car park buildings. Two incidents occurred in public type parking buildings, one in a Swedish underground car park and another in a UK multi-storey car park. The other four incidents occurred in what appear to be private car parks.

A fire incident in a multi-storey car park in Preston (Lancashire, UK) caused damage to 100 m^2 of concrete structure (Anon, 1991). Three cars received severe damage and six other cars suffered heat and smoke damage. This fire started in the engine compartment of a parked car. The fire was finally extinguished by fire-fighters, who had to wear breathing apparatus due to the smoke accumulation at the low level above the floor.

More than 100 cars were destroyed in an underground car park in Sweden in 1992 (Arvidson et al., 1997). The rapid flame progress across the ceiling was reported to have caused the fire spread between the cars.

Another underground car park fire in Austria in 1996 (Arvidson et al., 1997) caused the loss of 14 cars and severe structural damage. The fire-fighters initially could not reach the seat of the fire due to the intense heat and zero visibility. Seventeen occupants in the residential flats above the car park suffered smoke inhalation and were given medical treatment.

Lambert (1999) reported a similar fire incident in a basement car park measuring 15 m by 30 m, under residential units in New South Wales, Australia. There were five cars in the basement; fire destroyed three cars and damaged two others before it was brought under control by fire-fighters. Large volumes of smoke and zero visibility were reported. Severe structural damage, including concrete spalling and the dislodging of concrete slabs, was caused by the intense heat produced by this basement vehicle fire.

Pentony and Manser (2002) reported a fire incident also in New South Wales, Australia, which happened in an open deck car park measuring 50 m by 20 m, under three levels of apartments. The car park was also divided by steel wire mesh into 38 separate garages. The fire started in a garage on the south side and progressed to seven other garages, causing damage to cars, stock and structural components. The opposite residential units, at a distance of 3.2 m from this building, also received damage caused by radiant heat. The article recommended the installation of a sprinkler system in the parking building. The authors also concluded that the fire can spread between parked vehicles in an open car park and that the belief that fire contained only within single vehicles in an open car park, should be revised. Garrad (2002) stated that sufficient ventilation and the control of material combustibility are critical for fire safety in the design of parking buildings as demonstrated by this fire, although it does not justify the provision of sprinklers.

A recent fire, reported by James (2003), occurred in a car park within a non-sprinklered building in Australia. The building contained an enclosed car park accommodating 11 vehicles, a laundrette on the ground floor and six two-storey residential townhouses above. The fire was caused by the self-heating of cotton hand towels stored in the car park, and then spread to an adjacent car with ultimately three vehicles becoming involved in the fire. A smoke alarm was activated in one of the units above the car park. This fire resulted in $75,000 (Australian dollars) worth of property damage and $100,000 worth of vehicle damage. It was reported that fire-fighters experienced great difficulty in locating and extinguishing the fire due to the poor visibility. The report finally recommended upgrading of the vehicle exhaust ventilation system in the car park, the installation of appropriate passive fire protection at duct work penetrations, and the maintenance of existing smoke alarms in the building.

The case studies presented above highlighted the extent of hazard by vehicle fires in parking buildings to both human life safety and property protection. In particular, that smoke generated by the burning vehicles poses a great danger to life safety. The following photos in Figure 1-1 visually demonstrate the severity of burning and the amount of smoke generated from a single vehicle fire.

Figure 1-1: Car fire photos (Photo by Wayne Tomblinson www.amazingfirephotos.com)

1.4 Active Fire Protection Systems in the Parking Building

1.4.1 Roles

For the purpose of reducing life and property loss in the event of a fire, fire risk management is necessary and generally involves three main phases according to the time sequence (Ramachandran, 1998):

- Before the fire – fire prevention
- During the fire – appropriate actions to provide occupants with essential assistance to reach a place of safety
- After the fire – salvage operations, repairs to building damage and resumption of activities interrupted by the fire incident

The appropriateness of the provision of an active fire protection system for a parking building is assessed and determined in the first stage of fire risk management, which is fire prevention.

Fire prevention generally first involves identification of ignition sources and combustible materials. The next step in this phase would include the fire risk assessment carried out either qualitatively or quantitatively. If the fire loss is assessed to reach an unacceptable level, the reduction or possible elimination of the ignition sources is considered. Alternatively, fire prevention measures can be adopted to assist the occupants to safely evacuate the building and reduce the extent of fire damage to property in the event of a fire.

For a parking building, vehicles parked within are the main ignition sources and combustible objects. Unlike fixed objects in the building structure, the number of vehicles coming into the parking building is a constantly changing variable. Therefore the provision of fire prevention measures is more suitable to provide the protection required for both human life and property for this situation.

These fire prevention measures consist of both passive and active control. Passive fire control is generally built into the structure of the building such as fire rated partitions and protected steel work etc., whereas active control is achieved by actions taken by human or automatic devices. The active fire control measures usually include automatic sprinklers, automatic smoke detectors and alarms, smoke control systems and manual fire fighting devices. Automatic sprinkler and smoke control systems are the commonly adopted active fire protection measures for parking buildings.

Water is the most common agent used in automatic sprinkler systems, mainly because it is readily available, economical and non-toxic to humans. Though not necessarily extinguishing the fire, the operation of sprinklers can at least cool the environment, control the fire and protect the building until the fire can be suppressed by other means.

Sprinklers can decrease the fire risk to property and life by reducing property damage, and controlling fire spread extent and the probability of flashover. Therefore for a sprinkler protected building, some codes allow the reduction in fire resistance rating, an increase in building and compartment size, and an increase in evacuation time or escape route length.

In a building with both sprinklers and smoke control systems installed, there might be some interaction between the two systems. In the event of a fire, the water sprayed by the activated sprinklers tends to reduce the buoyancy of the combustion product and counter the outward flow through the vent.

1.4.2 Views from Literature

Described in this section are references from historical literature expressing opinion on active fire protection systems in parking buildings, especially the underground car park. These arguments are mainly about the suitability of providing automatic sprinkler and smoke control systems in parking buildings to achieve the protection of both life and property.

Parnell (1985) stated that a mechanical extraction system, instead of the natural venting method, should be adopted for smoke control design for an underground car park.

Turner (1986) discussed the importance of sprinkler systems installed in the underground car park in terms of the life safety of the fire-fighter and occupants. The author argued that in the event of a vehicle fire, the mechanical ventilation system could supply the fresh air and result in a faster growing and more severe fire. Operation of the sprinkler system would reduce the air temperature and also prevent the fire spreading between parked vehicles.

Stead (2000) also discussed fire brigade’s insistence of sprinkler provision in an underground car park as part of a development in Portsmouth, UK. It was argued that there is a rather high likelihood of fire spreading between closely parked vehicles, especially in a confined space and the smoke control system might not even be able to extract the smoke produced by a single burning vehicle.

Horton (2000) stated that the provision of compartmentation and sprinklers in the car park do not necessary guarantee a safe fire-fighter access. In this article, the use of an addressable automatic fire detection system with an auto-dialler function was recommended, in order to allow the early notification of fire to the fire service.

1.4.3 Code Requirements

1.4.3.1 Acceptable Solution C/AS1 – New Zealand

In New Zealand, the mandatory provisions for building work are contained in the *New Zealand Building Code (NZBC)*; the relevant clauses for fire safety in buildings are C1, C2, C3 and C4. In particular, the requirements for fire safety in car parks are laid out in clauses 6.10.3 to 6.10.6, in Part 6 (Control of Internal Fire and Smoke Spread) of *Acceptable Solution C/AS1* (New Zealand Building Industry Authority and Standards Association of New Zealand, 2000).

The spaces for car parking within a building are required to be separate firecells, which have to be constructed with fire rated floors and supporting structures.

If a car park firecell is not protected by sprinklers and smoke control in car park is not by natural cross-ventilation, the following requirements are to be met:

- Entry to any safe path or protected shaft has to be preceded by a protected path
- Specific fire engineering design is required for smoke control measures
- A type 3 alarm system has to be installed for a car park having more than 10 parking spaces. Type 3 alarm refers to automatic fire alarm system activated by heat detectors and manual call points

The natural cross-ventilation is provided by two opposite walls having openings to the open air. The size of these openings is at least 1/2 of the area of each wall, while at least 1/2 of the wall area with openings is to be evenly distributed along a length of no less than 1/2 the total wall perimeter.

These requirements from the *Acceptable Solution C/AS1* imply that for an underground or closed parking building, the sprinklers may not be required provided other relevant requirements are satisfied. For an open parking building, which is cross-ventilated with at least two opposite sides, there is no specific requirement placed by code in terms of the provision of fire protection systems.

1.4.3.2 NFPA 88A – the US

NFPA 88A (National Fire Protection Association, 1998) covers the construction and protection of both open and enclosed parking structures. Automatic sprinkler systems are not required for open parking structures, which are defined in the standard as those structures having more than 20% of wall area open to atmosphere at each level and utilising at least two sides of the building. Automatic sprinkler systems are required in parking structures with ceiling less than 2 ft (0.61 m) above grade for basement and underground parking structures. Automatic sprinkler systems are also required in enclosed parking structures of type III or IV construction over 50 ft (15.2 m) in height as well as in enclosed parking structures located within or immediately below another occupancy. A type III or IV construction refers to the building type with non-combustible or limited-combustible exterior structural materials, and entirely or partially wood interior structural members. A parking structure not meeting the classification of an open parking structure is considered enclosed. In enclosed parking structures, either a sprinkler system or a fire detection system combined with the mechanical ventilation system is required.

1.5 Objectives of Research

This research started with the risk analysis for vehicle fires in New Zealand parking buildings based on the historical data. The quantified risk assessment for vehicle fires in a parking building was then performed using event tree analysis. Finally a cost-benefit analysis was carried out for provision of the sprinkler system in a parking building.

Marchant (1990) also suggested a quantitative fire engineering approach for multi-storey car parks to be developed, based on the existing available data for car fires and buildings. This article recommended devising a range of fire scenarios assigned with appropriate probabilities. Various features of car parks such as parking layout, openness of the building, provision of the sprinklers and potential fire losses, were also recommended to be included in the model.

There were therefore three fundamental objectives in this research, which were:

- To obtain the characteristics of vehicle fires in New Zealand parking building from study of fire statistics
- To obtain fire frequencies for different fire spread scenarios by event tree analysis of vehicle fires in the Parking Building
- To develop a cost-benefit analysis model for the provision of a sprinkler system in a parking building and perform the analysis using this model

The first objective was achieved by analysing the statistical data from New Zealand Fire Service Fire Incident Reporting System (FIRS). The results included the frequency of vehicle fires in parking buildings, the type of parking building where vehicle fires occurred, the causes of vehicle fires in parking buildings, the frequency of the vehicle fire spread in parking buildings, type/age of vehicles involved in fire in parking buildings, day/time when vehicle fires occurred, heat source for vehicle fires and objects/materials first involved in fire.

The second objective was attained by setting up event tree models according to different fire spread scenarios or the number of the vehicles involved in a parking building fire. The initiating vehicle fire frequency in parking building was obtained from FIRS data and results of a survey done during this research about fire safety in New Zealand parking buildings. The relevant probabilities for branches in the event tree were obtained from the statistical analysis of New Zealand Fire Service FIRS data. Models were set up for both non-sprinklered and sprinklered parking buildings.

The third objective was accomplished by developing a cost-benefit analysis model using measure of cost-benefit ratio for the appropriateness of provision of an automatic sprinkler system in a parking building. Based on the results from event tree model, the relevant benefit and cost for the model were identified and determined as well as the discount rate. The model was applied to a case study using the Monte Carlo simulation in @RISK programme where the sensitivities of various inputs were also analysed.

1.6 Outline of Report

This report consists of seven chapters. Chapter 2 provides the literature reviews for car fire severity tests, car fire tests in parking structures, vehicle fire related modelling, sprinkler tests in parking structure, statistics of vehicle fires and parking building fires and fire risk analyses.

Chapter 3 deals with the first objective of this research and presents the analyses of FIRS statistics for vehicle fires in New Zealand parking buildings. Chapter 4 handles the second objective by setting up the event tree model for vehicle fires in New Zealand parking buildings, based on the results from Chapter 3. Chapter 5 deals with the third objective and presents a cost-benefit analysis of the provision of sprinklers in New Zealand parking buildings from the perspective of the parking building owner.

The conclusion and recommendations from this research are given in Chapter 6 and Chapter 7 respectively.

Chapter 2 Literature Review

2.1 Experiments on the Severity of Vehicles Fires

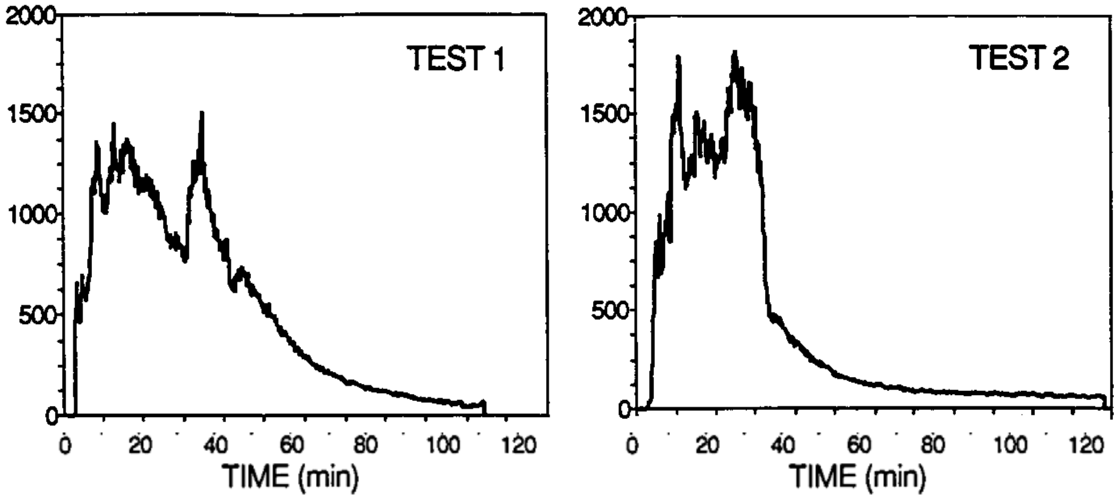
2.1.1 Mangs and Keski-Rahkonen (1994a) – Finland

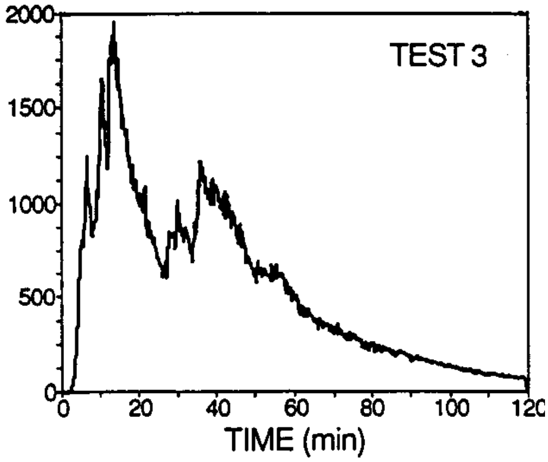
Mangs and Keski-Rahkonen (1994a) described three full scale fire tests on three medium size passenger cars manufactured in the late 1970's. The test car was placed on an indoor weighing platform, with a steel tray on the top to collect liquid spill. The combustion products were collected by a hood connected to an exhaust duct where gas samples were taken for analysis.

In Test 1, one of the doors of the test car was left open slightly and all the windows were fully open. In Test 2 and 3, all the doors of the test car were shut; one window was completely open with the rest of the windows partially open.

The car in Test 1 was ignited by a tray of heptane positioned under the left front seat in the passenger compartment, while in Test 2 and 3 a tray of heptane under the engine compartment was used for ignition. The cars in all three tests were left for a complete burnout after ignition.

The heat release rate (HRR) and mass loss rate were reported along with heat fluxes and temperatures for various locations in each test. The measurements of carbon monoxide, carbon dioxide and smoke production rate were also given in the article. The HRR as a function of the time and model of cars are shown in Figure 2-1.





No.	Vehicle
Test 1	Ford Taunus 1.6
Test 2	Datsun 160J Sedan
Test 3	Datsun 180B Sedan

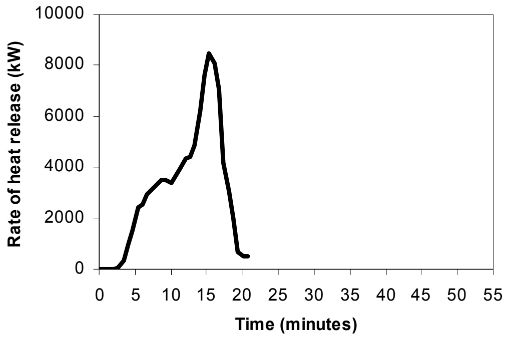
Figure 2-1: HRR (kW) vs time (min) for three 1970's car fires, reproduced from Mangs and Keski-Rahkonen (1994a)

2.1.2 Shipp and Spearpoint (1995) – the UK

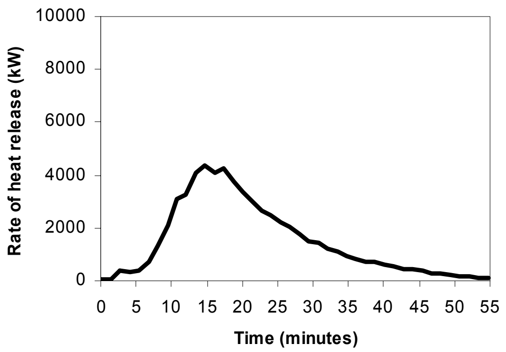
Shipp and Spearpoint (1995) presented results from two full scale fire tests on private motor vehicles, commissioned by Channel Tunnel Safety Unit, Department of Transport in UK to assess fire safety in the Channel Tunnel shuttle train. To represent the worst case fire scenario in a shuttle wagon, the test car was placed under a canopy with two sides surrounded by insulated steel cladding. Two calorimeters were connected to both ends of the canopy as shown in Figure 2-2. A tray was used to collect the spill of flammable material from the burning car.

Two medium range cars used in tests were a 1982 model Austin Maestro and a 1986 model Citroen BX. Both cars were loaded with some luggage and papers and the fuel tank was three-quarter full. The front windows of test car were left open while doors were all closed. Sufficient ventilation was provided into the canopy for both tests.

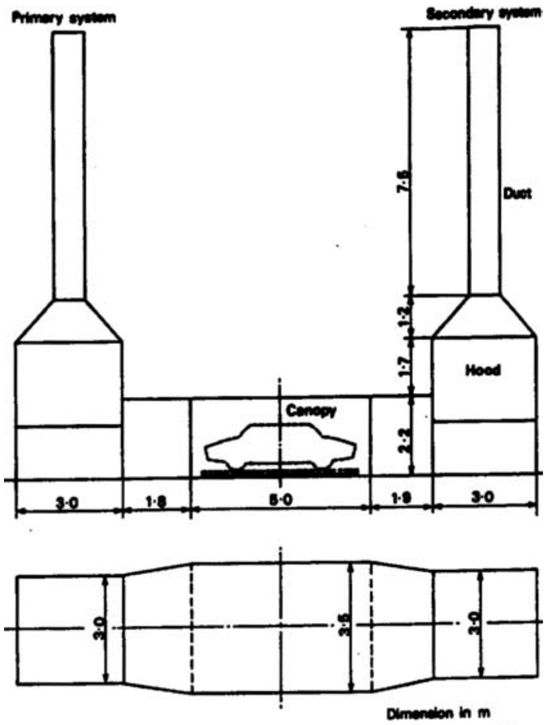
The Maestro car was ignited by No. 7 crib (BS 5852: Part 2: 1982) within the passenger compartment. This fire became intense after 13 minutes, due to the spill of petrol from fuel tank. The smoke overflowed out of the experiment rig and flame entered the duct causing the loss of some instrumentation. The fire was extinguished after 17 minutes. The Citroen was ignited by a tray of petrol placed in the engine compartment. In the latter test, fire was not as severe. It was allowed to develop for 57 minutes, and then extinguished.



Maestro test (seat ignition)
with petrol spill



Citroen test (engine ignition)



Canopy and duct configuration

Figure 2-2: HRR (kW) vs time (min) for two 1980's car fires and rig layout, reproduced from Shipp and Spearpoint (1995)

The parameters reported for each test involved HRR, burning rate, gas and surface temperatures in and near the car, heat fluxes caused by radiation, toxic product concentrations and smoke density. Figure 2-2 shows the HRR as a function of the time for both tests.

Visibility reached hazard level in less than five minutes for both tests, according to the measurements of toxic product concentration. For the first Maestro car test, authors concluded that if there was another car parked at 1 m from the test car, it could have ignited after approximately 10 minutes due to radiation from the test car.

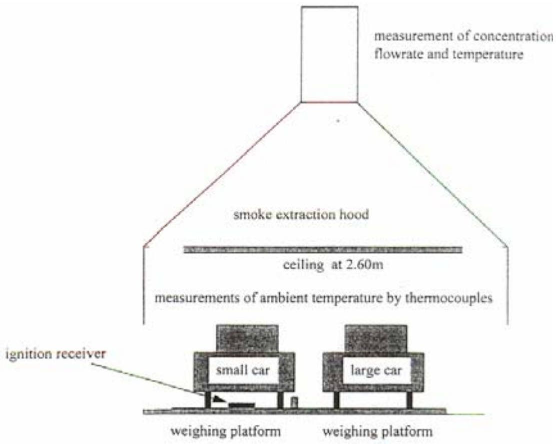
2.1.3 Schleich et al. (1999) – Europe

In 1995 and 1996, CTICM in France performed a total of nine car fire tests (Schleich et al., 1999) in a calorimeter hood as shown in Figure 2-3; it could accommodate two cars and simulated a closed car park. The tests involved different ventilation conditions and burning of one or two cars in a single test. The test cars were placed on a weighing platform; the combustion products were collected by a hood above the car park. Some steel members were placed in the calorimeter hood, and their conditions observed when exposed to vehicle fires.

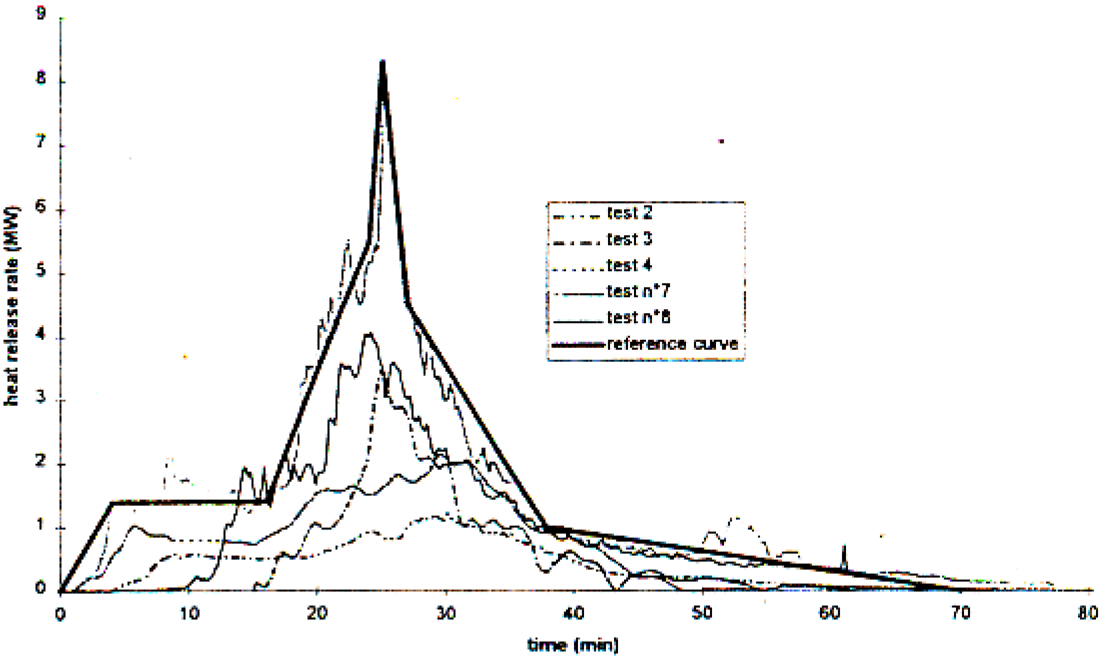
The condition of all the test cars was as in normal use with petrol tank two-thirds full. In the first seven tests, the car was ignited by a tray of petrol placed under the left front seat. The left front window was fully open, while the right front window was left half open. In the last two tests, the ignition was started with 1 litre of petrol under the gear box; this was also a test procedure adopted by some car manufactures. The doors of cars were closed for all nine tests.

The measurements taken for each test included HRR, mass loss rate, heat fluxes, steel temperatures, gas temperatures and toxic products. The first six tests involved cars manufactured during the 1980's and new cars were used in Test 7, 8 and 9. The tests showed that the energy released by a car made in 1995 was twice that of a 1980's car. Some of the HRR results can be found in Figure 2-3.

Calorimeter hood



Configuration for Test 9



HRR (MW) vs time (min) for five car fire tests and proposed reference curve

Figure 2-3: Test configurations and HRR curves, reproduced from Schleich et al. (1999)

Based on these tests, the report introduced an HRR reference curve for fire engineering design. This curve is shown in Figure 2-3 with the test results. A "wave" theory was also proposed in this report to account for the fire spread between multiple vehicles in a closed car park. According to this "wave" assumption, the cars will burn one after another, with a delay time of 12 minutes. By examining the HRR reference curve, one can infer that the fire of first car will start to decay when third car starts to ignite at around 24 minutes. It was also concluded that the fire can be confined within single vehicle with the provision of sprinklers or reliable detection system combined with adequate fire-fighting equipments.

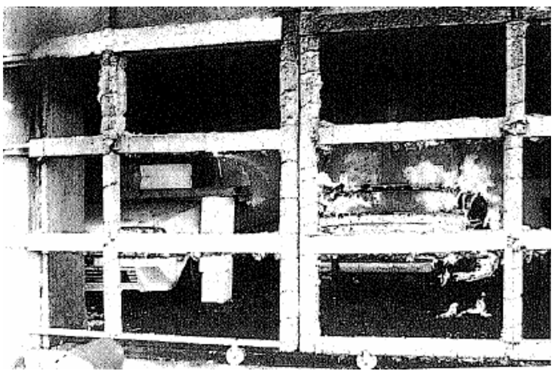
Table 2-1: Mass loss, total released energy in fire and mean car mass for 1996 European cars, reproduced from Schleich et al. (1999)

category	mass loss (kg)	released energy (MJ)	car mass (kg)
1	200	6000	850
2	250	7500	1000
3	320	9500	1250
4	400	12000	1400
5	400	12000	1400

The report classified the cars made in 1996 by European manufacturers into five categories as shown in Table 2-1; the mass loss and total released energy in fire and mean car mass were listed for cars in each category. The released energy in the table was based on a complete burnout of a car with a full fuel tank.

2.1.4 Steinert (2000) – Germany

Steinert (2000) reported a total of ten full scale car fire tests at MFPA, Germany. Cars ranging from one to three in each test were put in a closed compartment measuring 5 m by 7 m with a height of 4.5 m. A 10 m high chimney was installed in this compartment, which had an opening 2 m high and 3 m wide as shown in Figure 2-4.



Fire in Test 7

Smoke spilled out of the compartment in Test 8

Figure 2-4: Car fires photos for Test 7 and Test 8, reproduced from Steinert (2000)

Table 2-2 shows the number of cars, fire spread time and parking distance for each test. The cars in Test 1, 2 and 3 had different types of car body material. The ages of test cars were not reported.

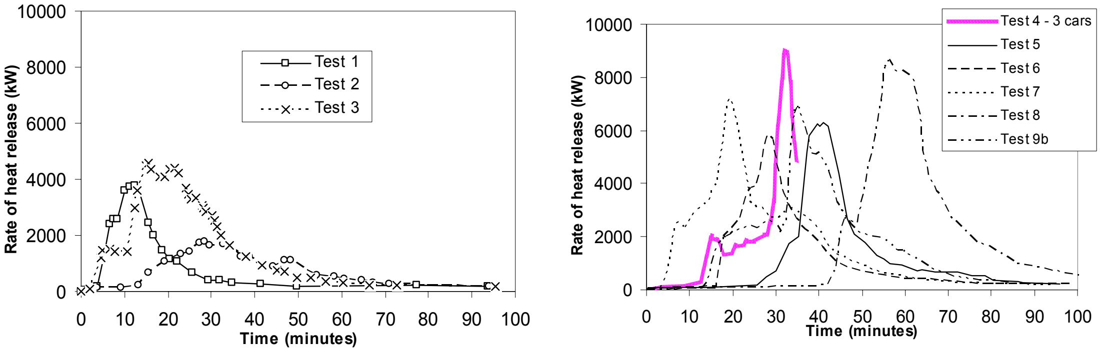
Table 2-2: Summary of ten car fire tests, reproduced from Steinert (2000)

Test No.	Number of Cars in a Single Test	Car First Ignited	Car Involved in Fire by Fire Spread	Fire Spread Time from Ignition (min)	Parking Distance (cm)
Test 1	1	Trabant	-	-	-
Test 2	1	Austin	-	-	-
Test 3	1	Citroen	-	-	-
Test 4	3	Golf	Trabant	30	80
			Fiesta	32	80
Test 5	2	Peugeot	Trabant	35	40
Test 6	2	Trabant	Polo	22.5	80
Test 7	2	Trabant	Citroen	12	80
Test 8	2	Ascona	Jetta	52	80
Test 9a	2	BMW	Citroen	No spread	80
Test 9b	2	Trabant	Citroen	28.5	80

In each test, one car was ignited first. In Test 4, which involved three cars, the fire spread from first to third from the top of the cars; this appeared to indicate that the fire reached flashover in the compartment. Fire in this test was manually extinguished at around 32 minutes to prevent the test compartment from damage. All other fire spreads were by ignition of the combustible materials on the side of the cars. Fire spread did not happen in Test 9a.

In Test 8, the smoke produced by car fire overcome the ventilation system and issued out of the compartment through the opening as shown in Figure 2-4.

The measurements for each test included temperatures, gas concentrations, heat fluxes, mass loss rate and HRR. Figure 2-5 shows the HRR curves for nine car fire tests. The HRR curve was not shown for Test 9a, where fire did not spread between cars during the experiment.



Test 1,2 & 3 – single car

Test 4, 5, 6, 7, 8 & 9b – multiple cars

Figure 2-5: HRR (kW) vs time (min) for nine car fire tests, reproduced from Steinert (2000)

It was also found from the tests that there are some linear correlations between the maximum HRR and the total energy to be released from the test car; Figure 2-6 indicates the gradient varying between 0.55 MW/GJ and 0.85 MW/GJ.

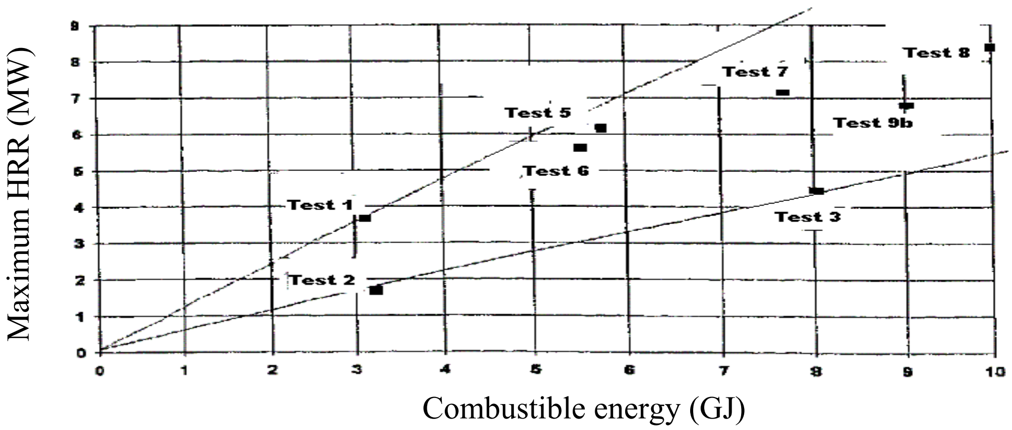
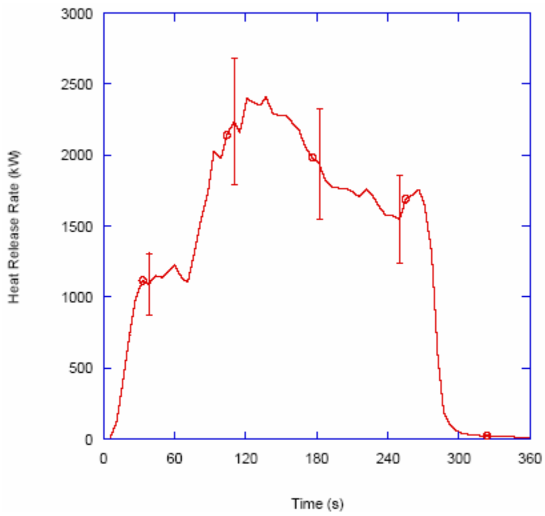


Figure 2-6: Correlation between Maximum HRR (MW) and energy (GJ) from car fire tests, reproduced from Steinert (2000)

2.1.5 Stroup et al., (2001) – the US

As part of a fire investigation by the U.S. Department of Treasury’s Bureau of Alcohol, Tobacco, and Firearms, two fire tests were carried out in a 1995 passenger minivan with some exterior damage. The experiment was conducted under a 4m by 5m calorimeter hood at NIST in the US.

In the first test, the windows were all closed and fire was started by ignition of approximately 0.317 kg of paper in the passenger compartment. The fire went out due to lack of the oxygen. In the second test, 2 litres of gasoline was ignited in the passenger compartment with the driver and passenger windows open. As the fire developed, the closed windows broke and fell out; the condition of burning at this point is shown by the photo in Figure 2-7. The fire was extinguished at approximately 4 minutes (240 s) after ignition. The HRR as a function of the time was shown in Figure 2-7, with a peak value of 2.4 MW. Temperatures and gas concentrations were also measured at various locations within the passenger compartment during the test.



HRR (kW) vs time (min)

Burning after the crack of front window

Figure 2-7: HRR (kW) vs time (min) for a minivan fire and a test photo, reproduced from Stroup et al. (2001)

2.1.6 Work by General Motors – the US

2.1.6.1 Fires with Ignition in the Engine Compartment

General Motors conducted a fire initiation and propagation test project under an agreement with the United States Department of Transportation. The objectives of this project were to examine the ignition mechanism of post crash vehicle fires and the fire severity.

As part of the project, three fire tests (Santrock, 1996, 2002a, 2003b) were performed on crash tested vehicles at Factory Mutual test centre to obtain the behaviour of fire spread from the engine compartment into the passenger compartment. The measurements taken for each test included air temperatures, heat fluxes and combustion gas concentrations all in the passenger compartment, as well as the HRR. Figure 2-8 illustrates the experiment setup for one of the tests (Part 3).

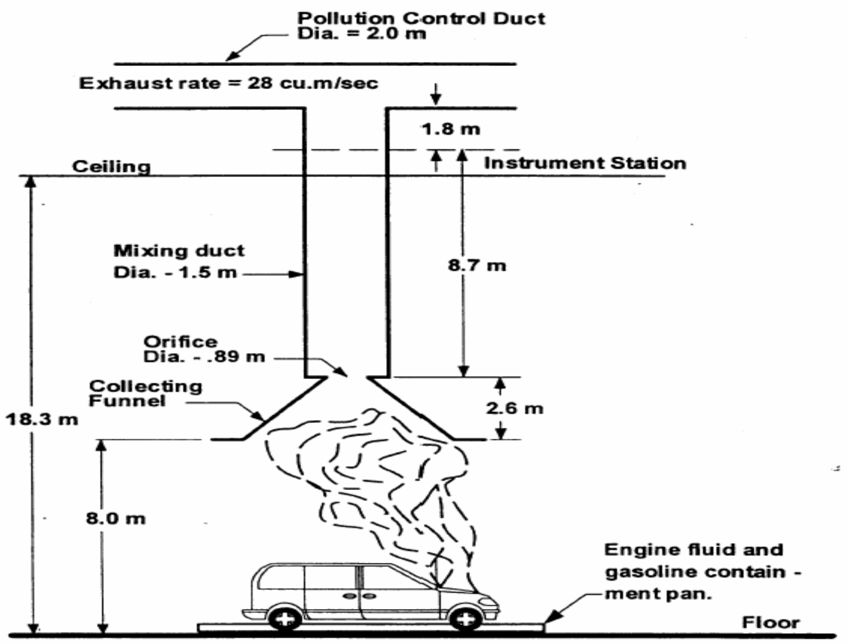
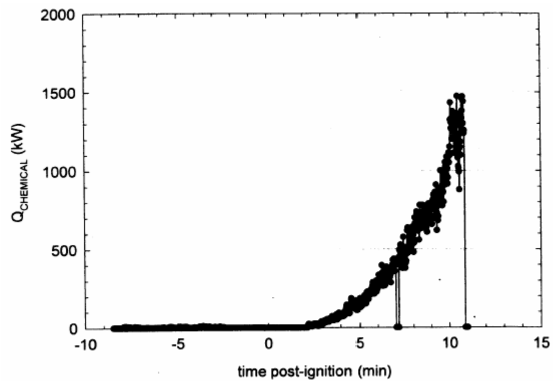
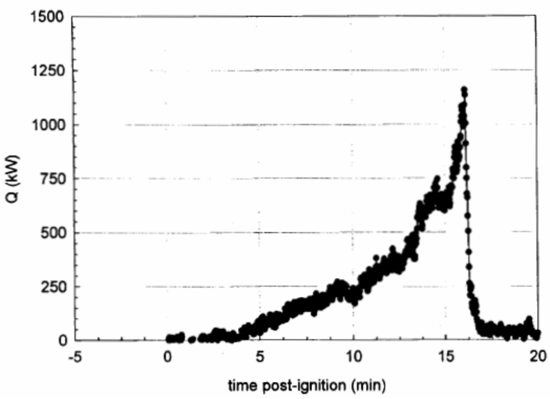


Figure 2-8: Fire products collector at the Factory Mutual test centre for test Part 3, reproduced from Santrock (1996)



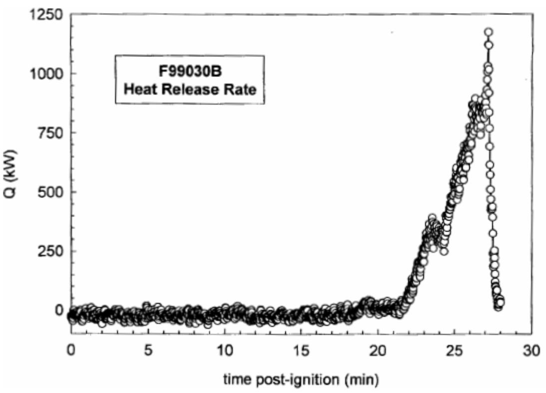
HRR(kW) vs Time (min) After the fire test

Test Part 3



HRR(kW) vs Time (min) Before the fire test

Test Part 7



HRR(kW) vs Time (min) Before the fire test

Test Part 13

Figure 2-9: HRR (kW) vs time (min) for vehicle fires with ignition in engine compartment, reproduced from Santrock (1996, 2002a, 2003b)

Table 2-3 summarises the test date, vehicle details, ignition method and fire extinguishing time for three tests. The recorded HRR and car photo for each of the three tests are shown in Figure 2-9. In each test, the fire was not allowed a full burnout and extinguished at some stage after the fire spread into the passenger compartment. Consequently the HRR did not reach the peak value and only show the growth phase.

Table 2-3: Summary of three vehicle fires with ignition in engine compartment

Report Part No.	Date of Test	Vehicle Details	Ignition Mechanism	Time of Extinguishment after Ignition
Part 3	November 13, 1996	I996 Dodge Caravan Sport	battery and power distribution ignited by an electrical ignitor	11 minutes
Part 7	October 1, 1997	1997 Chevrolet Camaro	A propane torch was used for ignition in the engine compartment	16 minutes
Part 13	February 23, 1999	1998 Honda Accord	ignition of methanol vapour in the windshield washer fluid reservoir by burning power steering fluid	27 minutes

2.1.6.2 Fires as a Result of Pool Fire under the Vehicle

As part of the project introduced in section 2.1.6.1, four other fire tests (Santrock, 2002b, 2002c, 2002d, 2003a) were done on crash tested vehicles to study the spread of an underbody fuel pool fire into the passenger compartment. The measurements taken for each test included air temperatures, heat fluxes, combustion gas concentrations, and the HRR. The experiment setups similar to that in Figure 2-8 were used. Table 2-4 lists the test date, vehicle details, ignition method and fire extinguishing time for four tests.

The measured HRR curve for each of these four tests is shown in Figure 2-10. Similar to other three tests introduced in section 2.1.6.1, the fire was not allowed a full burnout and extinguished at some stage after the fire spread from pool fire into the passenger compartment. As a result, the HRR did not reach the peak value and only show the growth phase.

Table 2-4: Summary of four vehicle fires initiated by underbody fuel pool fire

Report Part No.	Date of Test	Vehicle Details	Ignition Mechanism	Time of Extinguishment after Ignition
Part 6	September 30, 1997	1997 Chevrolet Camaro	Underbody gasoline pool fire	210 seconds
Part 9	June 9, 1998	1998 Ford Explorer	Rear-underbody gasoline pool fire	170 seconds
Part 10	June 11, 1998	1998 Ford Explorer	Mid-underbody gasoline pool fire	250 seconds
Part 12	February 25, 1999	1998 Honda Accord	Underbody gasoline pool fire	155 seconds

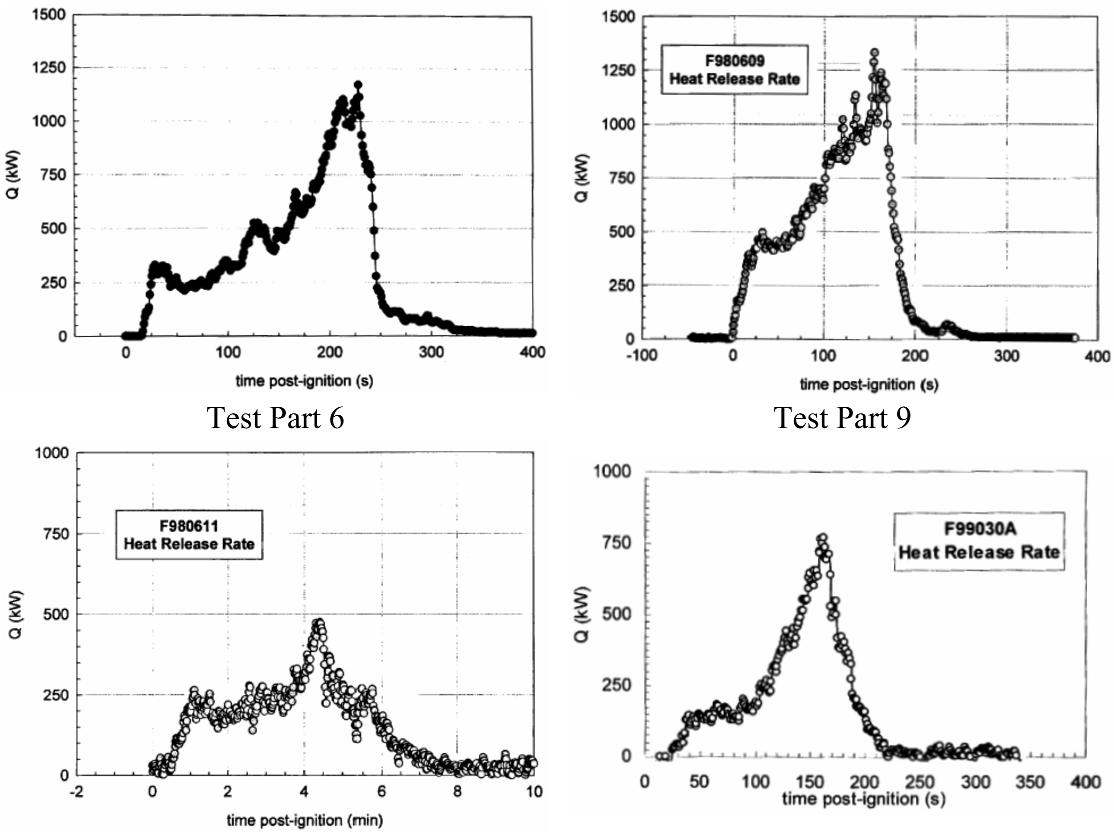
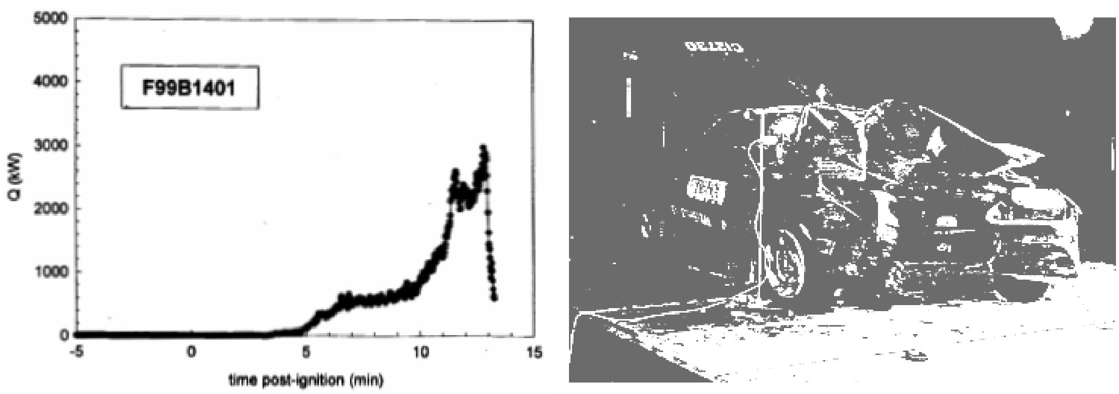


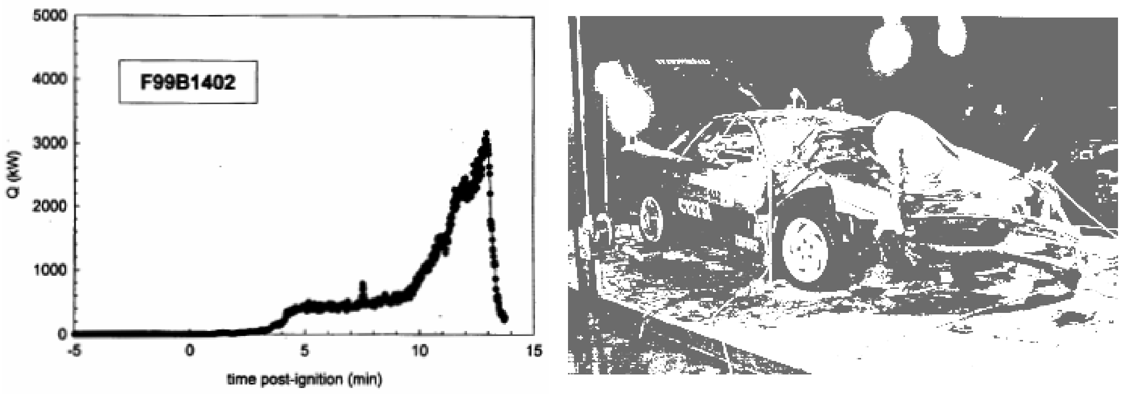
Figure 2-10: HRR (kW) vs time (min) for vehicle fires initiated by fuel pool fire, reproduced from Santrock (2002b, 2002c, 2002d, 2003a)

2.1.6.3 Fires with Flame Retardant Materials Involved

General Motors also conducted another project under the same agreement with the United States Department of Transportation. The objective of this project was to investigate the effects of substituting plastic resins containing flame retardant chemicals in the HVAC (heating, ventilation, and air conditioning) module.



Control Vehicle



FR Vehicle

Figure 2-11: HRR (kW) vs time (min) for fires of control and FR vehicles, reproduced from Santrock (2002e)

Two full scale fire tests were carried out on two crash tested 1999 Chevrolet Camaros cars (Santrock, 2002e). One vehicle was unmodified and designated as control vehicle, while another vehicle contained flame retardant chemicals in the HVAC module and designated FR vehicle. For both tests, the experiment setups, ignition methods and measurements taken were similar to the fire initiation and propagation test project reviewed in section 2.1.6.1 and 2.1.6.2. Both fire tests were extinguished at 13 minutes after ignition. It was found that the plastic materials containing flame retardant chemicals did not affect the behaviour of fire spread from the engine compartment into the passenger compartment. The measured HRR curves and test car photos taken before test are shown in Figure 2-11.

2.1.7 Small Scale Tests – the US

2.1.7.1 Work at NIST

A series of experiments were done to assess the fire hazard after a motor vehicle accident, under a cooperative research agreement between General Motors and National Institute of Standards and Technology (NIST) in the US.

The effectiveness of a passive fire protection technology involving intumescent paints and caulks was examined in simulated post crash vehicle fires (Hamins, 1998). It was found that the coating lowered heat conduction through the metal panel. However the coating failed to prevent the flames from penetrating holes, some of which were as small as 6 mm in diameter.

The data measurements for combustible liquids including fire points, flame height, heat flux and ignition time were taken to assess the fire behaviour following fuel spilling caused by motor vehicle crash (Ohlemiller and Cleary, 1998). Some selected combustible parts from a minivan were also burned and fire hazard parameters such as HRR, mass loss rate and heat flux were obtained (Ohlemiller and Shields, 1998).

2.1.7.2 Janssens et al. (2004)

Janssens et al. (2004) presented a small scale test methodology of rating automotive materials. The test was engaged by the National Highway Traffic Safety Administration (NHTSA) in the US. Eighteen exterior automotive parts from a passenger van and a sport coupe were tested in the cone calorimeter. Based on these test data, a model was shown to predict fire growth, for certain materials in post crash vehicle fires originating in the engine compartment.

2.1.8 Design Fire of Single Vehicle Fire

Table 2-5 lists a range of approximate maximum HRR values quoted by Ingason (2001) and Shipp (2002) for various types of vehicles. The HRR figures from Ingason (2001) were for the condition of road tunnel ventilation.

Table 2-5: Maximum HRR of vehicle fires, reproduced from Ingason (2001) and Shipp (2002)

Type of vehicles	Maximum HRR (MW)	
	Ingason (2001)	Shipp (2002)
Small passenger car	2.5	8
Large passenger car	5	
2-3 passenger cars	8	-
Van	15	-
Truck	-	17
Bus	20	-
School bus	-	30
Lorry with burning goods (general case)	20-30	-
Train	-	13-50
Subway coach	-	35
Heavy goods vehicle (HGV)	-	120
Petrol tanker	200	-

Figure 2-12 shows various HRR curves from the historical literature presented earlier (section 2.1), along with slow and medium t-squared fire HRR curves for comparison. The definition of t-squared or power law fire growth can be found in Chapter 2-2, *SFPE Handbook of Fire Protection Engineering* (DiNenno, 2002). The test reported by Mangs and Keski-Rahkonen (1994a) gave relatively low magnitude of HRR for all three tests, thus only Test 2 was chosen to represent this study. The study described by Schleich et al. (1999) was represented by the proposed reference HRR curve. Single vehicle fire test by Steinert (2000) yielded relatively low HRR, hence only Test 3 was shown to represent this work. The vehicle fire test carried out by Stroup et al. (2001) was not allowed a full burnout and hence not shown for comparison. Similarly, the tests by General Motors were also not shown (Santrock, 1996; 2002a, b, c, d, e; 2003a, b).

The HRR curve for Maestro car by Shipp and Spearpoint (1995) and the reference HRR curve by Schleich et al. (1999) show almost same peak HRR value (about 8 MW); this peak value is also higher than other tests shown in the graph. In fact, the Maestro car test involved fuel spill from the petrol tank and thus caused the relatively high HRR peak reached 10 minutes earlier than the reference HRR curve. The peak HRR values from other tests are all less than 5 MW.

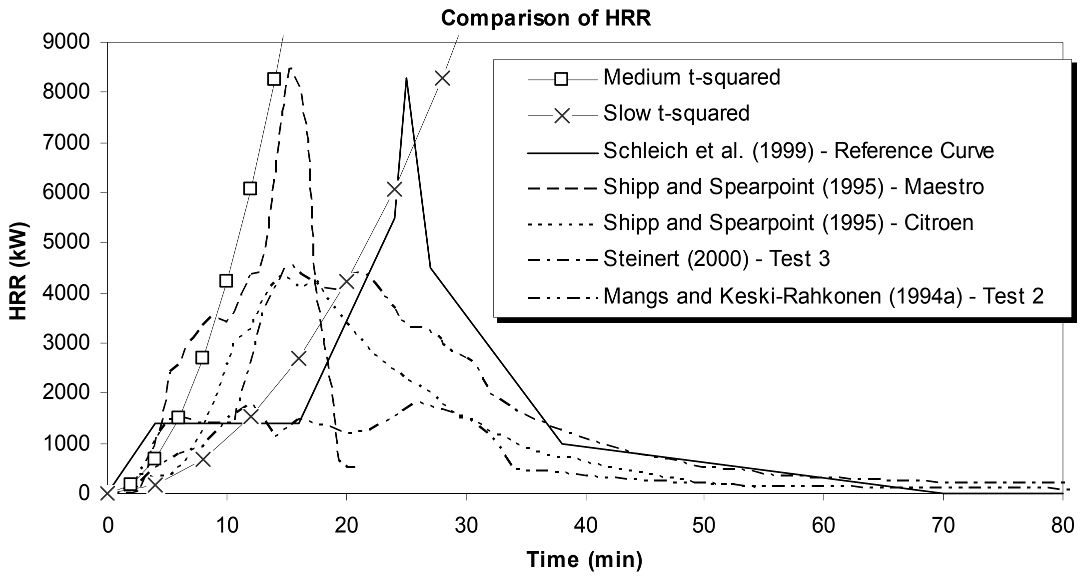


Figure 2-12: Comparison of HRR curves from various car fire experiments

From the Figure 2-12, it can be seen that the Maestro car HRR curve can be represented by a medium t-squared fire, while the reference HRR curve follows a slow t-squared fire. All other HRR curves fit between slow and medium t-squared fires. A growth rate between slow and medium seems to be appropriate for a t-squared vehicle design fires; a peak value of 8 MW can be used for a worst case scenario. It should be noted that the HRR data discussed here are for passenger vehicles only.

According to the HRR curves in Figure 2-12, there appears to be a trend that more modern cars yield a higher maximum HRR than old generation cars when involved in fire. Ingason (2001) observed a tendency of maximum HRR increasing linearly with the total energy to be released from passenger cars, and further proposed that an average increase of 0.7 MW in maximum HRR can be expected from one GJ of energy. This value is within the range of HRR vs energy (0.55 to 0.85 MW/GJ) shown by Steinert (2000).

Additional introductions about HRR data for transport vehicles and components can also be found in Chapter 3-1, *SFPE Handbook of Fire Protection Engineering* (DiNenno, 2002) where Babrauskas shows HRR curves for half a tram car and vehicle seatings.

2.2 Experiments of Vehicle Fires in Parking Structures

2.2.1 Butcher et al. (1968) – the UK

Butcher et al. (1968) reported three car fire tests in a specially built steel scaffolding structure shown in Figure 2-13, with an insulated ceiling approximately 2.1m above the floor. The two ends of the structure were left open for the first and second tests, and closed for the third test. Nine cars in a three by three array were arranged with parallel spacings ranging from 0.75 m to 1.2 m. The tanks of all tested cars were filled with 23 litres of petrol and a considerable amount of combustible material was also put inside the car to represent the luggage.

The car located in the centre was ignited first in each test. The windows of ignited car were all closed except for the driver seat window, which was left half open. After ignition, the flames were observed out of windows at 8.3 and 12 minutes for first test and second test respectively. The condition at two minutes before full development of the fire in Test 2 can be seen in Figure 2-13. The fire was reported burning through the fabric section of the roof for Test 3 where a small soft top saloon was used and wind velocity was higher than the first two tests.

General building assembly

Fire seen two minutes before full development in Test 2

Figure 2-13: Car fire test photos, reproduced from Butcher et al. (1968)

The temperatures of the hot air under the suspended ceiling and structural steel around the ignited car were recorded during the test. The highest temperatures of gas and steel were 840°C and 360°C respectively; these temperatures were both reached during Test 2. The temperature for any non-combustible structural element never reached the critical condition. The measurements of radiation from ignited car to adjacent cars and smoke density in the structure were also taken. Based on the visual observation, the smoke layer was primarily confined at ceiling level.

The conclusions from this report can be summarised as follows:

- A fire in a single parked vehicle is unlikely to cause uncontrollable fire spread within a car park
- The damage to the car park building is not critical, if the structure is built from non-combustible material with sufficient structural strength and appropriate durability

In this study, the wood equivalent fire load density for a car park was found to be 17 kg/m^2 based on a parking area of 18.5 m^2 allocated for each vehicle.

2.2.2 Burgi (1971) – Switzerland

Burgi (1971) reported three sets of car fire tests carried out in a factory building designated for demolition. This was a closed structure of irregular shape with an area of 525 m^2 and a ceiling height of 3.7 m. The sprinklers were installed to assess the effectiveness of the fire extinguishing system. The cars used in the test were all obsolete vehicles with petrol tanks two-thirds full. The front windows of the ignited car were left half open. The air temperatures inside the structure were measured during all tests.

Test 1 – Fire at 28 minutes after ignition

Test 3 – Fire at 1 minute 20 seconds after ignition

Figure 2-14: Car fire test photos, reproduced from Burgi (1971)

The first test involved three cars, parked with normal spacing between each, on a platform 1 m high. The centre car, containing a carton of combustible objects, was first ignited by electric soldering iron. The fire smouldered for 18 minutes, at which point windows broke and the fire became more severe (due to sufficient ventilation within the compartment). Sprinkler system was activated by fire at 28.5 minutes and two minutes later smoke completely filled the structure. The fire did not spread to the adjacent cars. Figure 2-14 shows the test condition at 28 minutes, which was a half minute before the sprinklers activated.

The second test involved two cars sitting on the floor with a parallel parking distance of 0.5 m. A torch was used for ignition of the test car. An immediate severe fire was observed after ignition. The sprinkler system operated at 40 seconds after ignition and water from the sprinklers carried the burning petrol towards the adjacent car, thus igniting the front tyre of this car. The activation of the sprinklers also increased the smoke spread.

The configuration of the third test was similar to the second test, except for the ignition which was started by petrol in a container placed under the car to simulate arson. The test condition at 1 minute 20 seconds after ignition can be found in Figure 2-14. Intensive fire development was observed in the ignited car; the fire was finally extinguished with foam. The side and left rear tyre of the adjacent car was damaged.

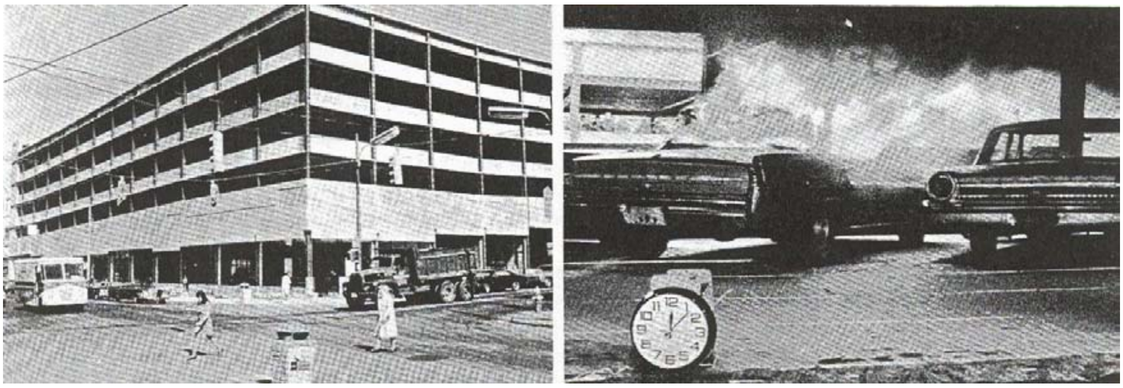
In this study, the fire development within a burning car was found to be dependant on the oxygen supply or ventilation condition in vehicle and ignition method. It was also observed that sprinklers cannot extinguish the fire inside the vehicle. The air temperature inside the structure was tolerable in terms of the tenability for human. Visibility was not impaired by smoke production until after the sprinklers activated, causing complete loss of vision within seconds.

The conclusion of this work can be summarised as follows:

- Smoke is the main hazard in a car park building in the event of a vehicle fire
- Automatic fire extinguishing systems may be necessary, depending on the type, size, location and available fire fighting equipment of the car park building

2.2.3 Gewain (1973) – the US

Gewain (1973) reported a full scale burnout car fire test sponsored by American Iron and Steel Institute. This was carried out in a multi-storey open air parking structure, constructed from unprotected steel frames and concrete decks, in Scranton, USA. The outside view of this parking structure is shown in Figure 2-15. The level just below the top level of the structure was used for this test. Cars were parked above the test level to provide the load on the structure.



Parking structure used for test

Burning vehicle with visible flame during the test

Figure 2-15: Car fire test photos, reproduced from Gewain (1973)

Three current model cars were used in the test, with all windows partially open to encourage the fire development. These cars were also loaded with combustibles and filled with 38 litres (10 gallons) of petrol.

The car at the centre was ignited first. The burning was then left uncontrolled and lasted for 48 minutes. Two other cars, which were parked less than 0.6 m (2 ft) from the test car, received minor damage. The author stated that the maximum steel temperature recorded during the test was 227°C (440°F) and well below the limiting temperature of 593°C (1100°F) as required by NFPA Standard No. 251 for such structural elements. The maximum air temperature was reported as 432°C (810°F) above the windscreen at 11 minutes after ignition; the air temperatures for most parts in the structure were below 204°C (400°F). Both deflection and elongation of the structural elements were recorded as zero after cooling. The author concluded that:

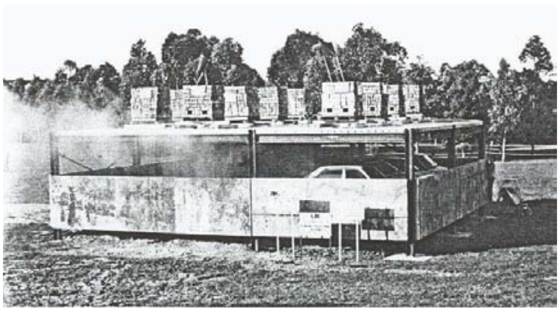
- There is a very low fire hazard in an open air parking structure
- Exposed steel provides adequate safety against the structure collapse under the circumstance of a car fire
- The results confirm those from similar tests by Butcher et al. (1968) and Burgi (1971)

The wood equivalent fire load density for a car park was found to be 9.8 kg/m^2 (2 lb/ft^2) in this report.

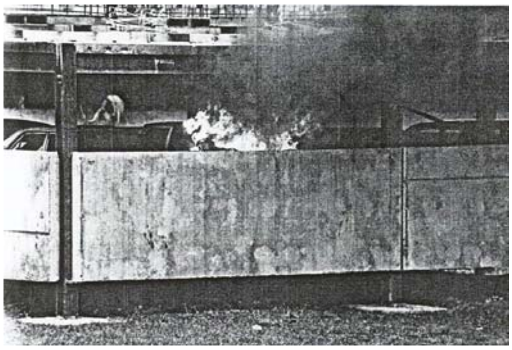
2.2.4 Australian Tests at BHP

2.2.4.1 Bennetts et al. (1985) – in Open-Deck Car Park

Bennetts et al. (1985) reported two fire tests in a two-level open-deck car park structure built from unprotected steel at BHP Melbourne Research Laboratories. The structure was loaded by placing concentrated loads on first floor, as shown in Figure 2-16. For both tests, five cars were parked on ground floor with a spacing of 0.4 m. The left front window of the test car was left half open. The petrol tanks were half full for all cars used in the test, except for the test car in second test, which was filled to 80%. The test car used in Test 1 had a steel fuel tank while the test car in Test 2 had a plastic fuel tank and an LPG tank. Both air and steel temperatures were measured throughout the two tests.



Open test structure



Fire in Test 2

Figure 2-16: Car fire test photos, reproduced from Bennetts et al. (1985)

In Test 1, the front windscreen broke at one minute after the ignition. The petrol tank filler pipe was involved in fire at 25 minutes. The burning of this car lasted for 70 minutes and fire did not spread to adjacent cars. Large amounts of pungent smoke were observed during the test.

In Test 2, windscreen and windows in the test car shattered soon after ignition. The fire spread from the car first ignited to two neighbouring cars at 14 and 35 minutes respectively. A photo taken during this test can be seen in Figure 2-16.

The maximum steelwork temperatures recorded were 285°C for Test 1 and 340°C for Test 2 respectively. The authors of this report concluded that a significant safety margin can be achieved with the unprotected steel structure under the fire situation in an open-deck car park.

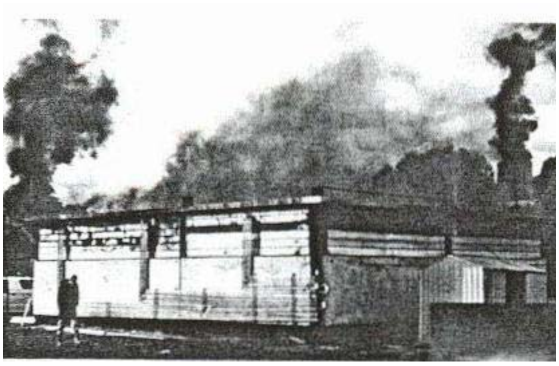
2.2.4.2 BHP (1987) – in Closed Car Park

A total of nine tests (BHP 1987) were performed in a closed car park building as shown in Figure 2-17, which was modified from the car park structure used in previous open-deck car fire tests. Twenty cars were used in these tests with various parking configurations; one photo in Figure 2-17 shows one of the vehicle arrangements. A sprinkler system was installed with a typical layout as permitted under AS2118 – 1982. A mechanical ventilation system was also installed in the test building. The measurements taken during the tests included inside air temperature, steel temperature, smoke optical density, carbon monoxide concentration, hydrogen chloride concentration and hydrogen cyanide concentration.

The fire in test car was initiated by igniting one kilogram of rag soaked with one litre of petrol under the front seat for all tests, except for Test 8 where the fire was started by the ignition of an open dish containing four litres of petrol placed under the petrol tank.

For five tests where the sprinkler system was operated manually, the fire burnt through the test car. In two of the tests where more recent cars were used, the fire spread from the test car to those cars parked at both sides and rear. The maximum temperature in steel reached above 400°C in these tests and smoke and toxic products were produced for a long period.

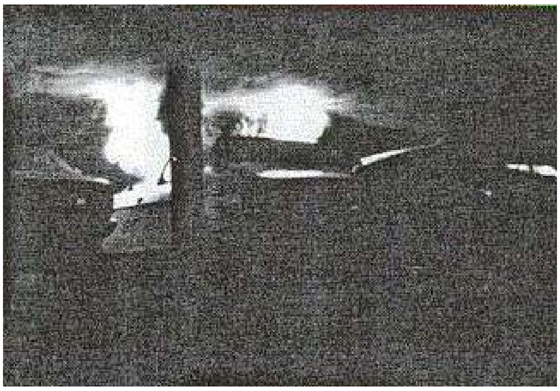
For the remaining three tests where the operation of sprinkler system was automatic, the fire was rapidly controlled and confined within the test car. The fire spreading between parked cars did not happen and the maximum steel temperature was less than 100°C. The amount and duration of the production of smoke and toxic products were also reported to have been reduced.



Closed test structure

Vehicles before the test with sprinklers installed overhead

Thick smoke emitting out of the structure during the test



View inside structure during the test

Figure 2-17: Car fire test photos, reproduced from BHP (1987)

Smoke was observed to fill the building rapidly in all eight tests and the subsequent untenable condition could pose a hazard to life safety; this can be seen from one photo in Figure 2-17. The conclusion reached in this report was that the sprinkler system was the major factor controlling the car fire development in a closed car park.

2.2.4.3 Bennetts et al. (1990) – in Partially Closed Car Park and Mixed Occupancy Building

Bennetts et al. (1990) reported a series of 14 fire tests, carried out at BHP Melbourne Research Laboratories, in a structure constructed from unprotected steel to simulate a building containing an office floor over a car park. A range of openings in the building were tested in this program to represent a partially closed car park.

The first three tests involved five cars with the fire ignited in one car; there were 30 litres of petrol left in the tank. Recent model cars were chosen at the time of the experiment. The following 11 fire tests were achieved by burning measured quantities of petrol in open dishes located at each side of the car park to investigate the effect of the different ventilation conditions in the structure.

A sprinkler system was installed in the building; the ventilation of the building was by natural means. Similar to the tests in a closed car park (section 2.2.4.2), the measurements taken in this test program included inside air temperature, steel temperature, smoke optical density, carbon monoxide concentration, hydrogen chloride and hydrogen cyanide concentration. The large quantity of black smoke generated in fire was observed in all the tests; this can be seen from the photo on left in Figure 2-18 for a test using five vehicles.

Smoke produced from car fire issuing out of the car park structure

Flame and smoke reaching the office window above the car park

Figure 2-18: Car fire test photos, reproduced from BHP (1990)

In this report, the authors concluded that:

- There is no need for fire protection of the steel work in a partially closed car park with a functioning sprinkler system
- The conditions in the partially closed car park in this test program were similar to those found in the closed car park
- One should treat a car park, not complying with the requirements for an open deck structure, as a closed car park when determining fire protection measures

A further two tests, where the fire was started in various locations in the office above the car park, were also reported (BHP, 1990) from the same test program. It was found that the office fires did not present a hazard to the car park structure below, due to the fact that the direction of spreading of heat and flame through the window was upward. It was therefore concluded in the report that the requirement for a supporting structure to have equivalent fire resistance to that which it supports, as set in the Building Code of Australia, is not suitable for structural components appropriately separated or in different compartments.

2.2.5 Schleich et al. (1999) – Netherlands

Two full scale tests (Schleich et al., 1999) were performed in a semi-closed concrete car park in Amsterdam, 1996. This car park was a concrete structure measuring 55 m by 85 m with a height of 3 m.

Three cars more than ten years old were parked in parallel as shown in Figure 2-19, with separation distances at 0.5 m and 0.7 m between the cars. The fuel tank of the middle car was half full; the other two cars had 10 litres of petrol in the tank. The fire was started from middle car by ignition of fuel in a steel tray underneath the front seat. The measurements taken during the test included gas temperatures under the ceiling, heat fluxes at various positions and mass loss rate of the middle car.

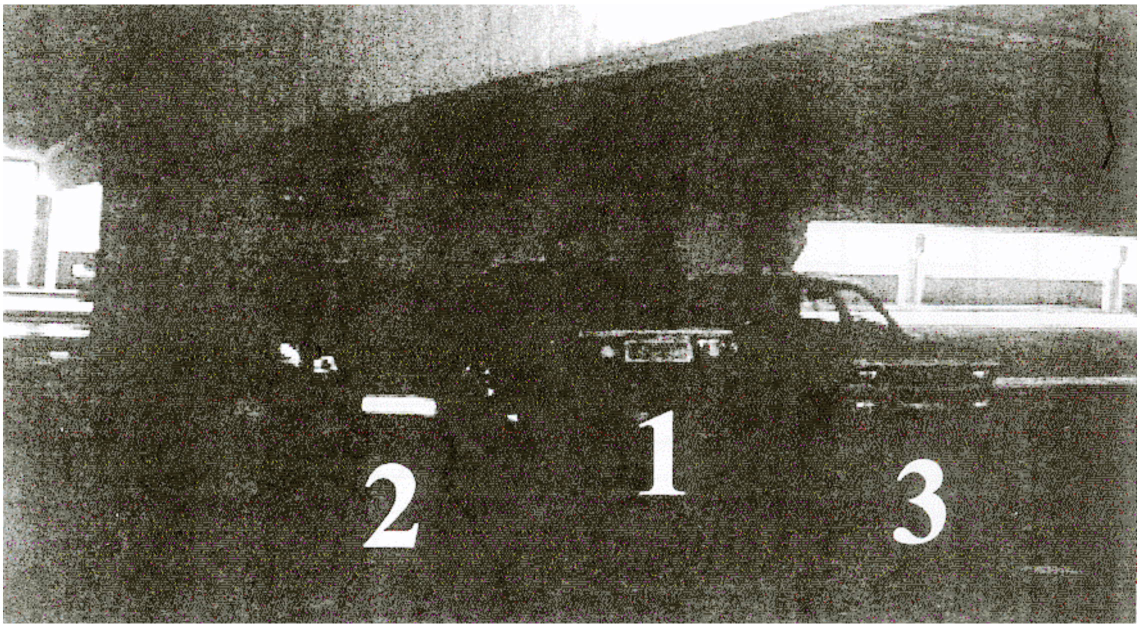


Figure 2-19: Car fire test photo, reproduced from Schleich et al. (1999

In Test 1, the windows of all the cars were closed. Consequently, the fire in the test car went out within three minutes of ignition due to oxygen depletion.

In Test 2, one window on each side of the test car was half open to allow adequate ventilation. Within eight minutes, fire in the first car spread to second car parked 0.5 m away. Ignition of the second car started with window rubber and tyre. At 15.5 minutes, fire spread to car on the other side. Visibility was reported as very low at this time. The fire-fighters extinguished the fire at 17.5 minutes after the ignition of first car. The authors suggested that parking distance could determine the time needed for occurrence of fire spread between cars.

2.2.6 Anon (2000) – France

CTICM built a two-level car park using unprotected steel work and concrete slab construction in Vernon, France and conducted a full scale fire test in this structure (Anon, 2000). The car park shown in Figure 2-20 measured 15 m by 32 m; the height between two levels was 3 m.

Three up-market cars parked in parallel were used in the test. The middle car was ignited first by a tray containing 1.5 litres of heptane under the gearbox. The measurements taken during the test included: ambient temperatures in the vehicle and structure, temperatures of the structural elements, vertical and horizontal displacements of the structural elements exposed to the fire, wind velocity and orientation.

Purpose built open car park structure

One minute after the ignition

Nine minutes after the ignition

Twenty-one minutes after the ignition

Figure 2-20: Car fire test photos, reproduced from Anon (2000)

At four minutes after ignition of the middle car, the fuel tank was involved causing spill of preheated fuel on the ground. The fire then spread to two other cars parked on both sides. The fire development was most severe from three to ten minutes after ignition; during this time flame was seen extending out of the car park and reaching one or two metres above the upper level of the structure. The fire started to decay at 15 minutes after ignition and was close to extinction at 35 minutes after ignition. It was considered that the wind condition had contributed to the rapid development of fire spread. The progress of the fire can be seen from photos in Figure 2-20.

The average temperature inside vehicles was around 900°C during the test; the temperature recorded at 10 m from the vehicles was about 250°C. The maximum temperature of steelwork reached 650°C in the lower flange of a composite beam above the test area; this temperature was recorded during the time period between 15 to 20 minutes after ignition. The beam exposed to fire showed a deflection of 40 mm after cooling; the breakage of three bolts was found on the end plate connecting the main beam and central column of the structure. Nevertheless, the report concluded that the stability of the structure was not affected, under the circumstance of this rapidly developing fire involving three vehicles.

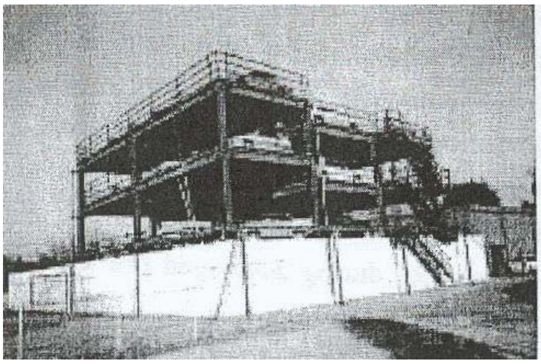
Another paper described a second test involving three vehicles in the same car park structure and gave the similar results (Kruppa and Zhao 2002).

2.2.7 Kitano et al. (2000) – Japan

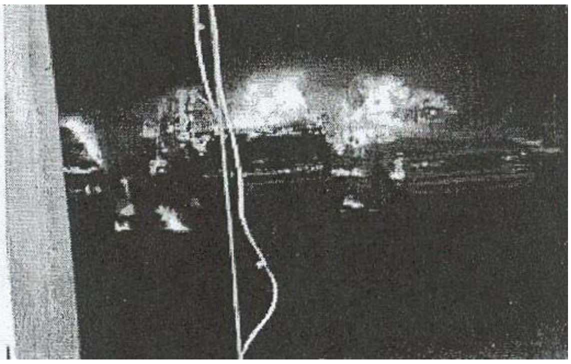
A large scale fire test was performed in a specially built car park structure in Japan (Kitano et al., 2000). This was a four-storey structure with a maximum height of around 10 m; the floor measured 30 m by 20 m. The structure as shown in Figure 2-21 was constructed from unprotected steelwork with two adjoining sides thermally insulated by autoclaved aerated concrete boards; the remaining two sides of the structure were left open.

In order to examine the burning behaviour of the vehicle and performance of the steel frame for the worst case scenario, 12 cars were placed at insulated corners on each level of the car park. These test cars were arranged as a two by six array.

The fire was started from a vehicle on first floor and finally involved seven other cars because of the radiation feedback from the ceiling and insulated wall. A photo showing the fire spread can be found in Figure 2-21. First fire spread occurred at 8.5 minutes and second and third fire spread happened at 19 minutes and 23 minutes respectively. The subsequent two fire spreads took place at 25 minutes; the final two fire spreads occurred at 43 minutes. The fire was extinguished shortly after this time.



Four-storey car park structure



Fire spread between cars during the test

Figure 2-21: Car fire test photos, reproduced from Kitano et al. (2000)

The steel temperatures were measured during the test; the maximum steel temperature was recorded as 700°C at the beam immediately above the car first ignited. The structural deflections were also measured and the deformations were found to be between 1/4 and 1/3 of the critical value. However the measured strain of one column reached the plastic region. The report concluded that the car park structure did not collapse under such a severe fire condition where a total of eight cars were involved.

2.2.8 Summary

Various car fire experiments from literature have been described in this section. The fire tests in open structures were reported by Butcher et al. (1968), Gewain (1973), Bennetts et al. (1985), Schleich et al. (1999), and Anon (2000). The fire tests in closed structures were described by Burgi (1971), BHP (1987), Bennetts et al. (1990), and Kitano et al. (2000). The sprinklers were installed in the tests reported by Burgi (1971), BHP (1987) and Bennetts et al. (1990). These car fire tests in structures were mainly trying to investigate:

- the behaviours of car fire and fire spread to adjacent cars in a parking structure
- the effect of car fires on structure of the parking building

- the performance of the sprinklers under the situation of car fires

These tests indicated that the fire can spread between the cars, especially in closed parking structures. The results from all the tests further showed the stability of the structure exposed to the car fires. The test results also highlighted the potential hazard to human life safety posed by large amounts of smoke produced in car fires, particularly in the condition of those closed type parking structures. The Australian tests (BHP, 1987; Bennetts et al., 1990) demonstrated the effectiveness of sprinklers to control the car fire development; whereas the Swiss test (Burgi, 1971) showed that the water from sprinklers shifted the burning petrol to adjacent vehicles.

2.3 Simulation and Modelling Based on Experimental Results

This section describes a number of studies, which were concentrated on simulation and modelling for the vehicle fire and its effect on structure. These studies used previous experimental results of vehicle fires either as input of the modelling or for comparison with the modelling results. Barber and Proe (2001) also presented some case studies of fire engineering design of parking buildings using published car fire test data.

2.3.1 Studies Based on the Severity of Vehicle Fires

2.3.1.1 Mangs and Keski-Rahkonen (1994b) – Finland

Mangs and Keski-Rahkonen (1994b) used two fire plumes, consisting of one at front window and another at rear window, to describe the car fire. One Boltzmann curve and three symmetrical Gaussian curves were then applied to represent the experimental HRR curves described in section 2.1.1 (Mangs and Keski-Rahkonen, 1994a). These parametric HRR curves were then used to calculate the gas temperature above a burning car, by Alpert's equations for maximum ceiling jet temperature. The calculation results showed good agreement with the experimental measurements (Mangs and Keski-Rahkonen, 1994a).

2.3.1.2 Kumar (1994) – UK

Kumar (1994) proposed a car HRR curve comprising an early slow growth phase and a later fast growth phase. The results of Maestro car fire test described in section 2.1.2 by Shipp and Spearpoint (1995) were used to calibrate and verify this HRR curve. The first growth phase represented the car seat first ignited during the test, while the second growth phase stands for the further involvement of the ceiling material and other seats within passenger compartment of the test car. The HRR curve was then used in a field model JASMINE to simulate the thermal and chemical characteristics of a vehicle fire in a Channel Tunnel shuttle wagon in transit. It was reported that the simulation results showed satisfactory agreement with experimental measurements from a full scale test involving car fires in a double decker shuttle wagon.

2.3.1.3 Schleich et al. (1999) – Europe

Schleich et al. (1999) presented simulations and results using CFD programmes (VESTA and FLUENT) to assess the behaviours of structure when exposed to vehicle fires in a closed car park. The input HRR curve in the modelling was based on work by Mangs and Keski-Rahkonen (1994a). Some design rules for steel structures were introduced for the situation of enclosed car parks as follows:

- Single vehicle fire – the unprotected steel structure with continuous composite beams is recommended
- Multiple vehicle fires – the steel structure needs to be composed of protected columns and unprotected continuous beams

2.3.2 Studies Based on Vehicle Fires in Parking Structures

2.3.2.1 Kruppa and Zhao (2002) – France

Kruppa and Zhao (2002) carried out two-dimensional modelling using programme SISMEF and three-dimensional modelling using programme ANSYS, to analyse the structural behaviour of the parking structure during fire test in car park described in section 2.2.6 (Anon, 2000). They compared the results of steel member deflection from numerical analysis with those from experiments, and concluded that the numerical analysis can conservatively predict the behaviours of structure exposed to vehicle fires as shown in the car park fire test.

2.3.2.2 Hirashima et al. (2003) – Japan

Hirashima et al. (2003) presented the two-dimensional structural analysis of thermal stresses and deflections for the fire test in car park (Kitano et al., 2000) as described in section 2.2.7. Similar to the result from experiment, the numerical analysis showed that the frame of car park structure used in the fire test did not collapse. The displacements of the steel frame from the numerical analysis also showed approximate agreements with the fire test results. This paper also concluded that the large curvature can develop at outer columns of the structure as a result of the thermal elongation of beam, if the frame is restrained for horizontal displacement at footings.

2.4 Experiments on Performance of the Sprinkler System in Parking Buildings

2.4.1 Stephens (1992) – the UK

Stephens (1992) reported three full scale sprinkler tests in a 30 m by 30 m area with a height of 9 m at Fire Research Station's Cardington Laboratory. The fire involved a number of double-decker buses (ranging from three to six) parked at a separation distance of 0.45 m, with three seats ignited simultaneously within one of the buses.

The sprinkler heads, installed in dry pipe system, were glass bulb type with temperature rating of 68°C and RTI of 200 $m^{1/2}s^{1/2}$. The results indicated that a discharge density of 14 mm/min was required to prevent the fire spreading between the parked buses, with ignition within one bus. However this discharge density did not restrain the fire spread within the burning bus. The discharge density of 5 and 10 mm/min failed to prevent the fire from spreading to adjacent buses. The test also showed that the time delay between sprinkler opening and water discharging from the system is a critical factor for the effectiveness of sprinkler system.

2.4.2 Arvidson et al. (1997) – Holland

Another full scale sprinkler test (Arvidson et al., 1997) was carried out in a bus garage in Holland in 1988. This was a structure with an area of 562 m^2 and sloped ceiling. The maximum ceiling height was 6 m and roof was divided into three smoke reservoirs. Three buses were parked at a gap of 1 m, with front doors open. The bus in the middle, with fuel tank two-thirds full, was ignited first. The fuel tanks of the other two buses were left empty.

The sprinkler system consisted of 40 sprinklers and each sprinkler covered an average area of 8 m^2. The sprinkler heads were of upright conventional type with solder links having a temperature rating of 74°C. A total of 12 sprinklers activated and the discharge densities varied from 14.4 mm/min to 22.5 mm/min. The fire spread to adjacent buses did not occur and the ceiling temperatures were reduced after operation of the sprinkler system.

2.5 *Statistical Studies of Vehicle Fires*

2.5.1 General Vehicle Fires

2.5.1.1 In the UK

Butler (1986) examined the causes and origins of the vehicle fires in Ireland and the UK, as well as the fatalities of young children in parked car fires. According to this article, fire brigades in Britain attended 45,000 motor vehicle fires per year, which caused approximately £45,000,000 worth of fire damage. Arson was reported to have caused 15% of motor vehicle fires. For non-collision vehicle fires, 35% of the incidents started from the passenger compartment and approximately 60% of the incidents originated in the engine compartment. In the UK from 1977 to 1982, there were nine children fatalities from eight fire incidents in parked cars, some of which were in parking buildings.

Chief-Inspector of Fire Service (1988) in the UK reported that the number of road vehicle fires almost doubled between 1976 and 1986 to 47,680. The cause for more than half (57%) of the vehicle fire increase was due to deliberate action or arson. Moore (1992) also reported the number of all vehicle fires in the UK having increased by 68% to 57,000, in a ten-year period from 1981 to 1990. In this article, the largest percentage of vehicle fires in UK was quoted to have occurred in vehicles of eight years old.

Based on the results of two surveys carried out in Lincolnshire in the UK, Moore (1989) listed the common causes of car fires as: electrical faults, fuel leaks/draining down of fuel tanks, welding or hot cutting and carelessness. Arson was not included in these causes. Whitaker (1989) also analysed the details of vehicle fire statistics in the UK and claimed that the collection of additional details for incidents is required, to show the vehicle fire cause and trend more clearly. Sandel (1991) discussed the details of petrol igniting on hot surfaces and recommended more accurate measures of reporting the vehicle fire causes. In 1999, the cause of 70% of road vehicle fires in the

UK was attributed to deliberate ignition except for buses (Shipp, 2002); this happened mainly on parked vehicles.

Chandler and Shipp (1995) described a statistical study to assess the fire safety provisions for the Channel Tunnel shuttle trains, based on fire statistics in the UK. The minimum estimated risks were reported as one death per every 600 fires and one injury per every 100 fires. The fire frequency in car carrying shuttle trains was estimated as one to three fires per year. The fire risks to life safety in the Channel Tunnel were also shown in this study as one death in every 1,500 years and one casualty in every 200 years. The article also suggested that the occurrence of fire is not time related if a vehicle engine has been kept on or off for more than 20 minutes.

2.5.1.2 In the US

A study (Trisko, 1975) was commissioned by the Insurance Institute for Highway Safety in the US to survey 51 participating fire departments to investigate national motor vehicle fires. The categories examined were origin of fire, age of vehicle, make of vehicle and collision related incidents.

Tessmer (1994) analysed fire occurrence in fatal and less serious crashes, considering characteristics of crash, vehicle involved, and driver. The analysis was based on the statistical data from the Fatal Accident Reporting System (FARS), Michigan Police Accident Report (PAR), and National Accident Sampling System Crashworthiness Data System (NASS CDS). Light trucks were found being more susceptible to be involved in fires than cars or vans. The older cars were more likely to be involved in post crash fire than newer cars. A car hit in the rear in a fatal crash is approximately 3.4 times more likely to have a severe fire than one struck from the front. It was also found that a crashed vehicle with fuel leak is 52.8 times more likely to have a fire than a vehicle without fuel leak.

A report (Federal Emergency Management Agency, 2001) based on data from US Fire Administration’s National Fire Incident Reporting System (NFIRS) examined highway vehicle fires in the US in 1998. The leading causes of the vehicle fires were mechanical or design problems, while electrical wiring and fuel were leading forms of material ignited. Fires subsequent to the crash caused most vehicle related fatalities.

Ahrens (2001) investigated the trends and characteristics of vehicle fires based on data from National Fire Protection Association (NFPA)'s annual fire experience survey and the NFIRS. The types of the vehicles included passenger road, freight road, rail transport, water transport, air transport, heavy equipment and special. The report included the categories such as location of fire, causes of vehicle fire, areas of fire origin, forms and types of material first ignited, as well as the time of the incident.

Cole (1988) examined 233 vehicle fires and found that two significant causes were fuel leaks (94 cases) and electrical shorts (42 cases). The 94 cases of fuel leaks included 45 carburettor or carburettor inlet leaks.

2.5.2 Vehicle Fires in Parking Buildings

2.5.2.1 Harris (1972) – the US

Harris (1972) surveyed 1,686 automobile parking structures with a total of 778,000 parking spaces in the United States and Canada. This study was sponsored by American Iron and Steel Institute, which also sponsored the full scale car fire test in a real parking structure (Gewain, 1973) as described in section 2.2.3. There were 395 fires reported during the entire life span of these structures, dating back to 1912 for some of the buildings.

According to this study, there was no loss of life or injuries due to fire in the parking structures surveyed. A total of 27 fires caused damage to the building, four of which resulted in losses of more than $5000 US dollars (USD). The maximum damage reported was $50,000 USD. These fires caused a total loss of $130,000 USD on approximately $2 billion USD worth of parking buildings. The damage caused by the remaining 368 fires was confined to the vehicles parked in the buildings.

There were 23 fires causing damage of less than $5000 USD. The openness of the parking structures was reported for 12 incidents of these fires. Three fires occurred in open air parking structures, while nine fires occurred in closed parking structures (either above ground or underground).

According to this study, the sprinklers did not contribute to fire control. The report finally stated that the risk in parking structures is separate from other types of occupancies in terms of determining insurance rate for fire.

2.5.2.2 Denda, (1993) – the US

Denda (1993) studied over 400 fires in parking garages including multi-level structures in the US, based on the NFIRS data. 80% of the fire incidents involved vehicles. The remainder was caused by malfunction of equipment such as elevators and generators etc. and mistake by human error.

There were no fatalities in any of these fires, albeit five fire-fighters and three civilians were injured. None of the injuries were directly related with fire. Although observances of extensive smoke were reported for 47% of the parking garage fires, the breathing apparatus were reported to have prevented injury to the fire-fighters.

It was reported that 7% of the fire incidents involved multiple vehicle fires. Fire spreading mainly occurred between two adjacent vehicles, although one incident involved three cars simultaneously and another included four cars.

Statistically, this study did not find significant difference between influences of the structure openness on the amount of the smoke observed. The extensive smoke was observed in 43% of the below-grade or underground structures, and in 46% of the aboveground open structures. The report also indicated that the sprinkler system was not a significant factor for risk assessment of such fires in parking garages.

2.5.2.3 Scoones (1995) – Vehicle Repairers in the UK

Scoones (1995) reported 90 serious fires in vehicle repairers, which caused eight fatalities and a total loss of £16,341,530 from 1990 to 1994. Nearly half of the total losses were from 12 fires, with each loss totalling at least £250,000. The serious fires were those incidents involving fatalities or losses of £50,000 or more.

2.5.3 Summary

Various statistical studies from the historical literature have been described in this section for general vehicle fires and vehicle fires in parking buildings. Some results from these studies will be used to compare with those from statistical analysis of New Zealand data for vehicle fires in parking buildings, which is the first objective of this research.

The studies on general vehicle fires usually involved the subjects of fire frequency, fatality, fire cause, fire origin, and age of vehicles involved etc. The studies reviewed in this section indicate that arson, electrical faults and fuel leaks are the common causes for vehicle fires.

The studies on vehicle fires in parking buildings mainly concentrated in the areas such as fire frequency, casualty, fire spread, financial loss, and the effect of sprinklers and structure openness on fire. Two US studies on vehicle fires in parking buildings did not report any fatality and structure collapse caused by parking building fires involving vehicles. Denda (1993) found multiple vehicle fires involving up to four vehicles. As highlighted in various car fire tests from the literature, the hazard to life safety posed by the smoke generated in vehicle fires in parking buildings was also shown by Denda (1993). Both US studies did not consider the sprinkler system as a critical factor in the fire safety of parking buildings. Also the statistical studies did not show structure openness as having a strong effect on vehicle fires in parking buildings.

2.6 Fire Risk Assessments

Numerous countries have developed comprehensive fire risk evaluation methodologies, by which one can take the advantages of performance based building code. Bukowski (1993) reviewed the work done in the US, Japan and Australia and found remarkable similarities in the different countries' approach. These methods all start with classification of the building, its occupants and quantification of the design fires, then move on to predict the spread of smoke/gas, response of occupants, intervention to fire and outcome of fire. The article highlighted the need for collaboration, which could lead to further improvements and a single composite methodology of building fire risk assessment.

Shipp (2002) reviewed the fire risks in road and rail tunnels, in terms of the fire frequency and fire severity. This article also discussed both active and passive fire prevention measures required to reduce these fire risks in tunnels.

Spearpoint (1997) presented a cost-benefit model for the installation of smoke alarms in dwellings in the UK. The analysis defined the reduction in fatalities and injuries by smoke alarms as the benefit; the cost was identified as those expenses for installing and maintaining domestic smoke alarms. A discount rate of 6% was used in the model for a twenty-year period. The analysis considered various scenarios and found that the installation of smoke alarms could result in a reduction of 126 deaths and 2,237 injuries per year in the baseline scenario.

Stephens (1995) described a method of cost-benefit analysis for sprinkler protection. The annual loss without sprinklers was obtained from estimated average cost of a serious fire divided by the mean time between fires (MTBF). The reduced annual loss with sprinklers was determined in a similar manner; fire frequency was assumed to be the same for both scenarios in the article. The difference between these two losses and insurance premium reduction from the provision of sprinklers was defined as the benefit. The cost involved installation and maintenance of sprinkler system and was considered on a yearly basis.

Barry (2002) presented method of developing and evaluating fire loss scenarios by event tree analysis and quantifying the fire risks. Ramachandran (1998) has given detailed descriptions of cost-benefit analysis for fire protection measures. The comprehensive discussions of fire risk assessments can also be found in *SFPE Handbook of Fire Protection Engineering* (DiNenno, 2002), *Fire Protection Handbook* (Cote and Powell, 2003) and *Evaluation of Fire Safety* (Rasbash et al., 2004).

Chapter 3 Statistics of Vehicle Fires in New Zealand Parking Buildings, 1995 – 2003

3.1 Background

3.1.1 New Zealand Fire Service FIRS Statistics

This chapter provides an examination of the fire incidents which involved vehicles and occurred in parking buildings throughout New Zealand, during the eight-year period from 1995 to 2003. The analysis of these fire incidents was based on the vehicle fire statistical data extracted from Fire Incident Reporting System (FIRS) database maintained by New Zealand Fire Service.

The statistics are based on the financial year starting from July and ending in June; consequently the data analyses in this chapter are also presented in financial year instead of calendar year.

There were a total of 26,969 vehicle fires in New Zealand as recorded in FIRS database during the eight-year period from 1995 to 2003. These data, in spreadsheet form, were filtered to obtain fire incident data for vehicle fires in New Zealand parking buildings during this time period. The definitions of vehicle and parking building are explained in the following sections.

3.1.2 The Definition of Vehicle

A vehicle in this chapter refers to all vehicle types listed in the following groups under the category of Mobile Property Type as in *New Zealand Fire Service Fire Incident Reporting System Instruction & Coding Manual* (New Zealand Fire Service, 1995):

- Passenger, Road, Transport Vehicles
- Freight, Road, Transport Vehicles
- Special and Miscellaneous Mobile Property

The vehicle types in the following groups are not included in this research: Rail Transport Vehicles; Water Transport Vehicles; Aircraft, Hovercraft; Industrial and Agricultural Heavy Equipment; Forest Harvesting Equipment; and Military Mobile Property.

3.1.3 The Definition of Parking Building

FIRS database reports two categories of property use: General and Specific Property Use. There were some apparent inconsistencies between the General and Specific Property Use in the vehicle fire statistical data extracted from FIRS database. It was decided to use the Specific Property Use rather than the General Property Use to determine if a vehicle fire occurred in a parking building (N. Challands, *pers. Comm.*). It was assumed that the conflicts between the two property uses in the data did not affect the analysis substantially.

A parking building is defined with reference to the following codes as specified in the group of Mobile Property Storage and Parking, under the category of Specific Property Use (New Zealand Fire Service, 1995):

- 8802 – Public carpark: Single level - covered
- 8803 – Public carpark: Multi-storied above ground
- 8804 – Public carpark: Multi-storied below ground
- 8805 – Public carpark: Multi-storied above and below ground
- 8807 – Private fleet carpark: Car, Bus, Truck (Single level - covered)

3.1.4 Others Issues

There were a total of 101 recorded vehicle fires in properties with Specific Property Use recorded as covered parking buildings; however 99 of these vehicles fires were recorded as mobile property fires instead of structure fires in FIRS database. Consequently, the analyses for vehicle fires in parking buildings in this chapter were based on the available information from vehicle fires recorded as mobile property fires in the FIRS database. This resulted in fewer details for each vehicle fire, particularly the details of the parking building involved in fire, the performance of the fire protection system (if any) and the impact of the vehicle fire on the building. These details would otherwise have been reported in FIRS database, if the vehicle fires had been recorded as structure fires.

The FIRS database had been kept modified; as a result some code definitions appeared in the FIRS data and cannot be found in the *New Zealand Fire Service Fire Incident Reporting System Instruction & Coding Manual* (New Zealand Fire Service, 1995). These code definitions were then obtained from an electronic guide for FIRS database and communication with New Zealand Fire Service. The electronic guide, in Microsoft Access format, was also developed by New Zealand Fire Service and included code descriptions for most fields in the FIRS database.

3.1.5 Presentation of the Statistics

In this chapter, the statistical data for vehicle fires in New Zealand parking buildings are generally presented in the pie chart form for the eight-year period from 1995 to 2003. These data are based on the statistics on yearly basis and can be found in Appendix A of this report.

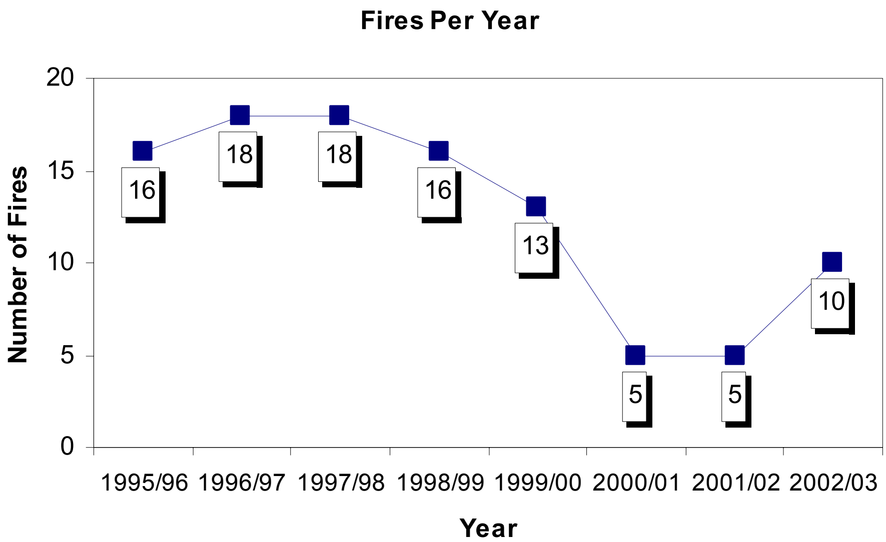
Unless noted, the number of vehicle fires quoted in this chapter is the number of vehicles involved in fire in parking buildings, as the details of the fire incidents were recorded per single vehicle in FIRS database. There were situations where multiple vehicles were involved in one incident and those details will be shown in section 3.5.

3.2 Number of Vehicle Fires in Parking Buildings and Casualties

On average, there were 3,371 vehicle fires per year in New Zealand during the eight-year period from 1995 to 2003.

From 1995 to 2003, the New Zealand Fire Service attended to total of 101 recorded vehicle fires in parking buildings, with an average of approximately 12.6 fires per year; the breakdown of fire incidents per year is shown in Figure 3-1.

There is no recorded fire fatality in parking buildings in New Zealand, although there were approximately two injuries of mainly minor burns each year caused by fires in parking buildings (A. Merry, *pers. Comm.*).



	Year				
	1995/96	1996/97	1997/98	1998/99	1999/00
Number of fire incidents	16	18	18	16	13
	Year			Total	Average per year
	2000/01	2001/02	2002/03		
Number of fire incidents	5	5	10	101	12.6

Figure 3-1: Number of vehicle fires in parking buildings, 1995 – 2003

During this eight-year period, there were a total of eight vehicles involved in three multiple vehicle fire incidents and the actual number of fire incidents in parking buildings involving vehicles was 96. Therefore, the average fire incidents in New Zealand parking buildings, where vehicles were involved, totalled 12 each year. Further details of fire spread will be discussed in section 3.5.

3.3 Specific Type of Parking Buildings Involved in Vehicle Fires

Figure 3-2 shows the breakdown of all vehicle fires in New Zealand parking buildings from 1995 to 2003, according to the building definitions in the group of Mobile Property Storage and Parking under Specific Property Use category (New Zealand Fire Service, 1995).

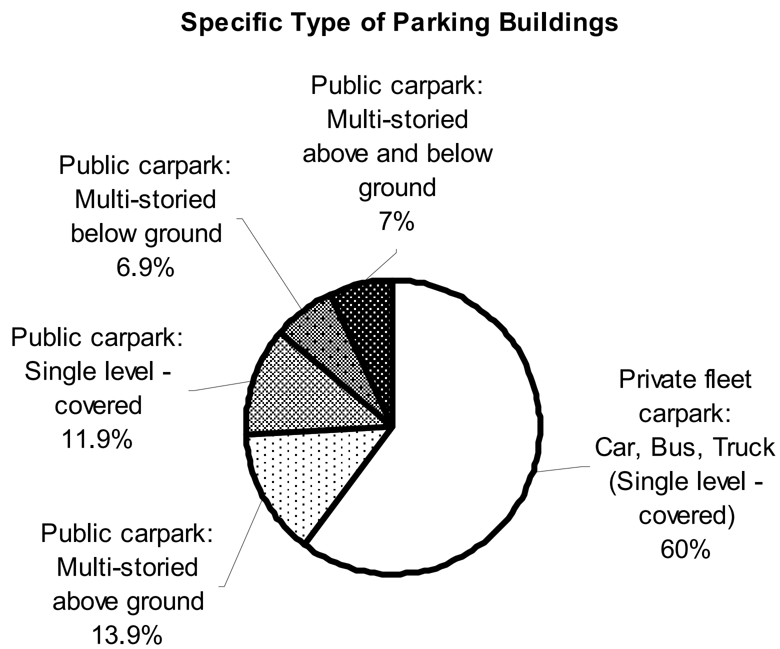


Figure 3-2: Specific type of parking buildings where vehicles were involved in fires, 1995 – 2003 (From Table A – 1, Appendix A)

The largest group of parking buildings where vehicle fires occurred was Single Level Covered Private Fleet Carpark, which accounted for 60% of all vehicle fire incidents or 61 incidents. This was also the only group for private parking buildings as defined in FIRS database.

Multi-storied above Ground Public Carpark were the second largest group, forming 13.9% of vehicle fires in parking buildings. This was followed by Single Level Covered Public Carpark (11.9%), Multi-storied below Ground Public Carpark (8.9%) and Multi-storied above and below Ground Public Carpark (7%). In total, the public parking buildings accounted for 40% of all vehicle fire incidents or 40 incidents.

In this statistical analysis, a public parking building was considered as the building any member of the public can get access to, while a private parking building was regarded as the building where the parking spaces are reserved for those specifically entitled to park there. It was supposed that fire-fighters held the similar view when entering the data into the FIRS database (N. Challands, *pers. Comm.*).

3.4 Supposed Causes of Vehicles Fires in Parking Buildings

3.4.1 Statistics in New Zealand

The supposed causes of vehicle fires in New Zealand parking buildings can be divided into two broad categories: Deliberately Lit fire and Accidental fire. The latter further includes five groups, which are Electrical Faults, Mechanical Failure or Malfunction, Carelessness, Unknown and Others. Figure 3-3 demonstrates the details of supposed fire causes, for vehicle fires in parking buildings from 1995 to 2003.

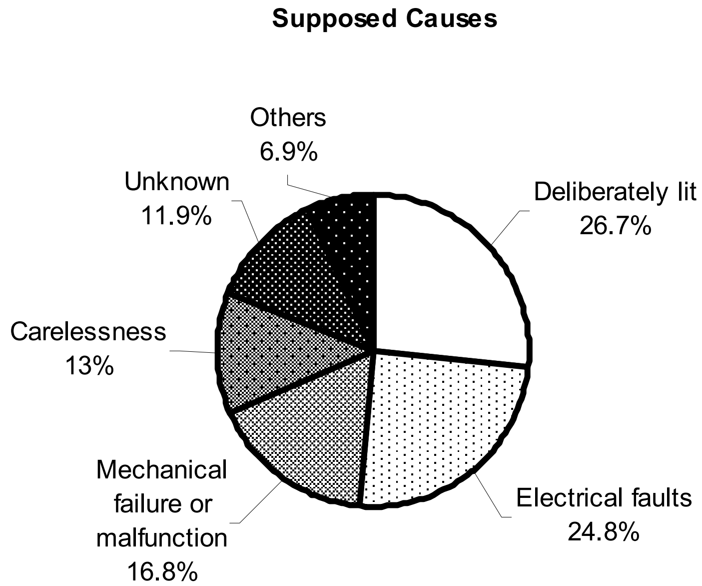


Figure 3-3: Supposed causes of vehicles fires in parking buildings, 1995 – 2003 (From Table A – 2, Appendix A)

The further breakdown of supposed causes of vehicle fires in parking buildings are explained below, in accordance with the descriptions under Supposed Cause category (New Zealand Fire Service, 1995)

The largest group of Supposed Cause was Deliberately Lit fires, which accounted for 26.7% of all vehicle fire incidents in parking buildings or 27 fires. This group included unlawful (15.8%) and suspicious (10.9%). The difference between unlawful and suspicious is the level of confidence in determining wether the fire cause is deliberately lit, when the incident data were coded into the FIRS database.

Of 61 vehicle fires in private parking buildings, 15 fires were deliberately lit, of which ten incidents were unlawful and five incidents were suspicious. There were therefore 46 accidental vehicle fires in private parking buildings.

Of 40 vehicle fires in public parking buildings, 12 fires were deliberately lit, of which six were unlawful and other six were suspicious. Hence the number of accidental vehicle fires in public parking buildings was 28.

The next two groups of Supposed Cause were Electrical Faults (24.8%) and Mechanical Failure or Malfunction (16.8%) respectively. The group of Electrical Faults involved short circuit and earth fault (19.8%) and other electrical failure (5%). The group of Mechanical Failure or Malfunction included part failure, leak or break (10.9%); equipment not being operated properly (2%); installed too close to combustibles (1%); other installation deficiency (1%); equipment overloaded (1%); and lack of maintenance (1%).

The following group was Carelessness. This group involved careless disposal (3%); heat source too close to combustibles (3%); combustible placed too close to heat source (2%); failure to use ordinary care (2%); reckless act (1%); people playing with heat sources (1%) and flammable liquid/gas spilled or accidentally released (1%).

The last two groups of supposed causes were Unknown (11.9%) and Others (6.9%). The group of Others included exposure fire (3%); backfire (2%) and friction (2%).

3.4.2 Comparisons with Overseas Findings

As discussed in section 2.5.3, the general statistics from overseas sources indicate that arson, electrical faults and fuel leaks are the common causes for vehicle fires. These finds are similar to the trend found in the New Zealand statistics in this research, where three leading fire causes of vehicle fires in parking buildings were deliberately lit, electrical faults and mechanical failure or malfunction. For New Zealand statistics, the cause of fuel leak was included in the group of mechanical failure or malfunction as shown in section 3.4.1. The comparison of vehicle fire causes between different countries can be found in Table 3-1.

Table 3-1: Comparison of vehicle fire causes

Rank	Fire Causes			
	New Zealand Parking Building Vehicle Fires (1995 - 2003)	**UK Vehicle Fires (1987)**	**US Passenger Road Vehicle Fires (1994 - 1998)**	**US Highway Vehicle Fires (1998)**
1	deliberately lit	deliberate/possible deliberate	part failure, leak or break	mechanical or design problems
2	electrical faults	electrical appliances & installations	circuit or ground fault	arson
3	mechanical failure or malfunction	oiled & petrol fuelled appliances and installations	incendiary or suspicious	carelessness

In 1981, three leading sources of ignition of vehicle fires in the UK ranked by the number of incidents were electrical appliances & installations, oiled & petrol fuelled appliances and installations, and deliberate/possible deliberate. In 1987, the cause of deliberate/possible deliberate became the leading source of ignition, followed by electrical appliances & installations and oiled & petrol fuelled appliances and installations (Whitaker, 1989). This 1987 figure in the UK appears to be similar to the New Zealand statistics in this research.

From 1994 to 1998, the three leading ignition factors of passenger road vehicles in the US were part failure, leak or break (18.8%); short circuit or ground fault (18.4%); and incendiary or suspicious (17.1%) according to the study by Ahrens (2001). The leading cause of highway vehicle fires in 1998 was mechanical or design problems, followed by arson and carelessness as the second and third cause respectively (Federal Emergency Management Agency, 2001). Again, the leading fire causes in the US were similar to those in New Zealand found in this research, although the fire causes ranked by the number of incidents were in different order for both countries. It should be noted that the statistics in this research are only for the vehicle fires in parking buildings.

3.5 Vehicles Fires in Parking Buildings by Number of Vehicles Involved

3.5.1 Records in New Zealand

The number of vehicles involved in fire was recorded in FIRS database in the form of Exposure Number. Every single vehicle fire has an Exposure Number of zero. A vehicle fire in the database, having an Exposure Number of one or greater, indicated that the fire was the result of exposure to an initial fire. However FIRS database did not indicate if the involvement of more vehicles contributed to the increase of heat release rate or those vehicles, recorded as involved in fire as a result of the fire spread, only received the minor damage from the vehicle first catching fire.

Figure 3-4 illustrates the vehicle fires in New Zealand parking buildings by number of vehicles involved due to a single ignition from 1995 to 2003.

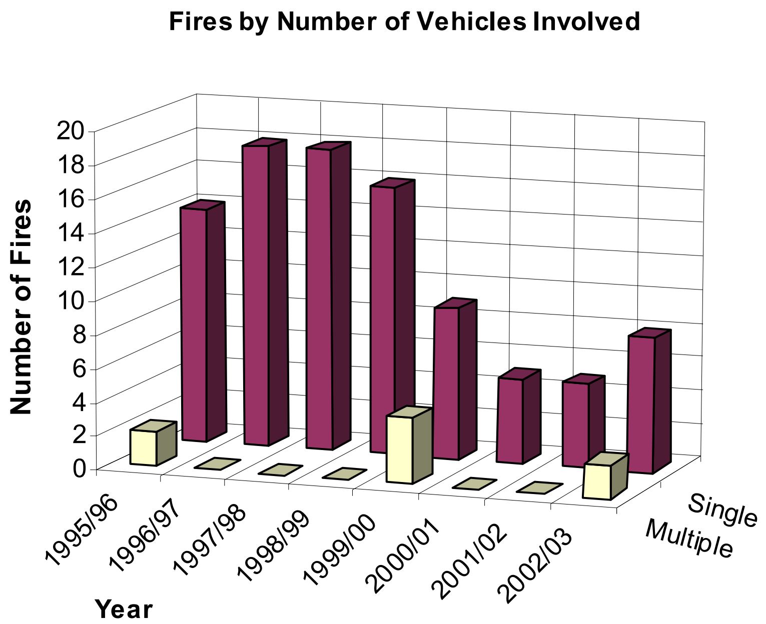


Figure 3-4: Vehicles fires in parking buildings by number of vehicles involved, 1995 – 2003 (From Table A – 3, Appendix A)

There were a total of eight vehicles involved in three multiple vehicle fire incidents during eight-year period from 1995 to 2003 and these fires all occurred in private parking buildings. During this period, there were a total of 101 vehicle fires in parking buildings; therefore the actual number of fire incidents in parking buildings involving vehicles was 96, which included 93 single vehicle fire incidents and three multiple vehicle fire incidents.

There were two incidents where two vehicles were involved in the parking building fire simultaneously; these two incidents occurred in the year of 1995/1996 and 2002/2003 respectively. One incident was caused by a deliberately lit fire, while the fire cause for another incident was accidental.

One other recorded incident involved four vehicles in the year of 1999/2000; this fire started from a vehicle with recorded type as light truck (under one tonne, ute, van, and wagon) then spread to three buses. The fire cause for this incident was accidental.

In summary, for eight vehicle fires where multiple vehicles were involved, two fires were deliberately lit and six fires were accidental. As found in section 3.4.1, there were 15 deliberately lit fires and 46 accidental fires in private parking buildings. Thus there were 13 deliberately lit non-spreading fires and 40 accidental non-spreading fires in New Zealand private parking buildings. There was no vehicle fire spread incident in New Zealand public parking buildings. These figures were used to determine the relevant probabilities in event trees which will be presented in Chapter 4.

3.5.2 Comparison with the US Study by Denda (1993)

There were three multiple vehicle fire incidents from a total of 96 fire incidents in New Zealand parking buildings, from 1995 to 2003. This means that approximately 3% of the vehicle fire incidents in New Zealand parking buildings involved multiple vehicles. This figure was lower than the 7% value quoted by Denda (1993) in a US study of more than 400 parking garage fires, which was described in section 2.5.2.2.

The same study by Denda (1993) found that most multiple vehicle fire incidents in the US parking structures involved two adjacent vehicles, with one case involving three cars and another involving four cars. The number of vehicles involved was similar in New Zealand parking building fires where two incidents involved two vehicles and one incident involved four vehicles.

3.6 Type of Vehicles Involved in the Parking Building Fires

Figure 3-5 illustrates the breakdown of type of vehicles involved in fire incidents in New Zealand parking buildings from 1995 to 2003.

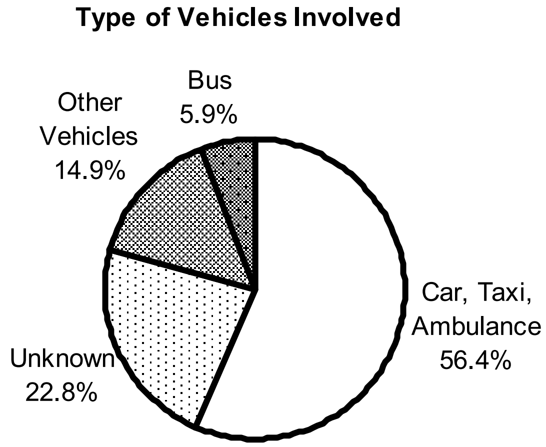


Figure 3-5: Type of vehicles involved in fires in parking buildings, 1995 – 2003 (From Table A – 4, Appendix A)

The further breakdown of the vehicle types are described as follows, according to descriptions under the category of Mobile Property Types (New Zealand Fire Service, 1995). The biggest group of vehicle types was Car, Taxi and Ambulance which account for 56.4% of all fires or 57 vehicle fires. This was followed by the group of Unknown (22.8%), Other Vehicles (14.9%) and Bus (5.9%). The group of Other Vehicles included truck of one tonne and over and fire appliance (9.9%); light truck under one tonne, ute, van and wagon (4%); and waste container, bin, compacter and dumper (1%) as described under Mobile Property Type category (New Zealand Fire Service, 1995).

3.7 Age of Vehicles Involved in Parking Building Fires

3.7.1 Figures in New Zealand

The FIRS database reports the year of vehicle fire incident and manufacture year of the vehicle involved. The manufacture year was recorded for 52 vehicle fires out of a total of 101 vehicle fires in parking buildings from 1995 to 2003. The ages of these vehicles were therefore obtained by subtracting the year of manufacture from the year of fire incident.

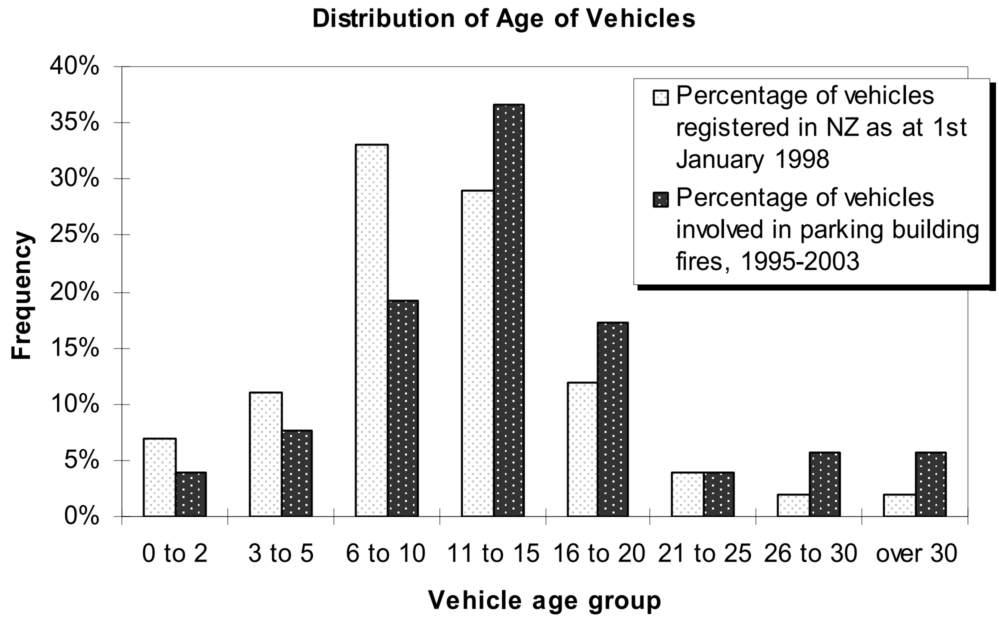


Figure 3-6: Distribution comparison between age of vehicles involved in parking building fires and age of all registered vehicles (From Table A – 5, Appendix A)

Figure 3-6 shows the distribution of recorded age of vehicles involved in New Zealand parking building fires from 1995 to 2003. For comparison, the age distribution for all registered vehicles in New Zealand as at 1st January 1998 (Tipping, 1998) is also illustrated in the same figure. It was assumed that the distribution of vehicle age for national fleet in 1998 can represent the trend in New Zealand in the eight-year period considered in this research. The correlation coefficient between two data sets of vehicle age was found to be 0.83.

The average recorded age of vehicles involved in New Zealand parking building fires was found to be 14.3 years old. The mean age for major vehicle types in New Zealand during five-calendar-year period from 1998 to 2002 (New Zealand Registrar of Motor Vehicles, 2003) can be found in Table A – 6, Appendix A. The average vehicle age in this five-year period was calculated as 14.2 years old and is very close to the average age of those vehicles involved in the parking building fires.

3.7.2 Comparisons with the Overseas Studies

Figure 3-6 shows that the vehicles of 11-15 years old were the largest group involved in parking building fire. Moore (1992) found that the largest percentage of vehicle fires in UK happened in vehicles of eight years old, which is less than the figure in New Zealand. This difference can possibly be due to the fact that the vehicle ages in New Zealand, with an average age of 14.2 years old, were generally older than UK.

Figure 3-6 indicates a correlation between the age of vehicle and probability of vehicle involved in fire. The percentage of vehicles involved in fires with ages less than 11 years old was lower than the percentage of vehicles in the same age group from national fleet; conversely, the percentage of vehicles involved in fire with ages equal to or more than 11 years old was higher than the percentage of vehicles in the same age group from national fleet. In conclusion, the probability of a vehicle involved in parking building fire rises with the increase of the vehicle age.

A 1973 national survey of motor vehicle fires in the United States (Trisko, 1975) found the similar trend and indicated that a vehicle of ten years old or more was four times more likely to be involved in fire than a vehicle less than three years old. In New Zealand from 1995 to 2003, a vehicle equal to or more than 11 years old was approximately two and half times more likely to be involved in parking building fires than a vehicle less than three years old. This value of 2.5 was obtained by dividing the percentage ratio for vehicles equal to or more than 11 years old by the percentage ratio for vehicles less than three years old; the percentage ratio for each age group was the ratio between the percentage of vehicles involved in fire and the percentage of vehicles from national fleet.

3.8 Vehicle Fires in Parking Buildings by Day and Time

Figure 3-7 illustrates the number of vehicle fires in New Zealand parking buildings by day of week, for eight-year period from 1995 to 2003. The number of fires was also broken down to private and public parking buildings, the definitions of which can be found in section 3.3.

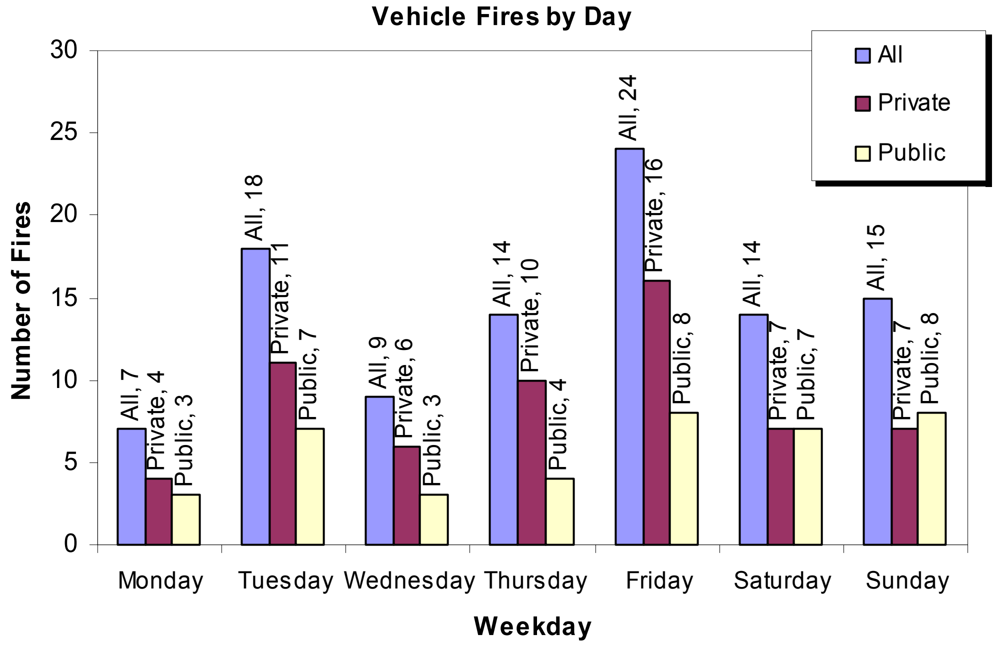


Figure 3-7: Vehicle fires in parking buildings by day of week, 1995 – 2003 (From Table A – 7, Appendix A)

It can be seen that Friday was the peak day of the week for total parking buildings as well as both private and public parking buildings. The fewest fires occurred on

Monday for total parking buildings and private parking buildings, while Wednesday was the day with the fewest vehicle fires in public parking building. It can also be seen that the vehicle fire frequencies in private parking buildings were generally higher than those in public parking buildings; however Sunday was the only day when the number of vehicle fires in public parking buildings exceeded that in private parking buildings.

Figure 3-8 demonstrates the number of vehicle fires in New Zealand parking buildings by time of day, for eight-year period from 1995 to 2003. The number of fires was also broken down to private and public parking buildings.

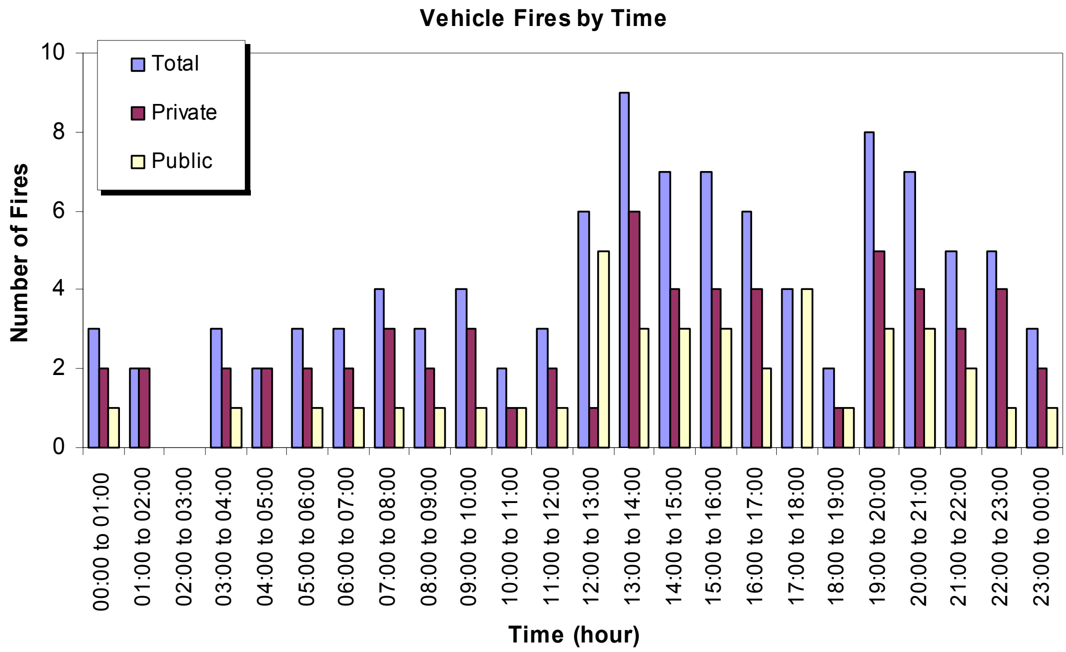


Figure 3-8: Vehicle fires in parking buildings by time of day, 1995 – 2003 (From Table A – 8, Appendix A)

The occurrences of vehicle fires in parking buildings appear to be related to the time of vehicle use. The low fire frequency occurred between 00:00 and 7:00 with a small increase from 7:00 to 10:00. No vehicle fires happened in parking building during 02:00 to 03:00 period. There was a slight drop of fire frequency between 10:00 and 11:00. The fire frequency then increased steadily as the time progressed, reaching peak between 13:00 and 14:00. From this point, fire frequency gradually decreased until the hour between 18:00 and 19:00. The fire frequency showed a sudden increase between 19:00 and 20:00, and then declined steadily during the 20:00 to 00:00 period.

During the time period from 12:00 to 13:00, the vehicle fire frequency in private parking buildings was lower than that in public parking buildings. There was also no vehicle fire in private parking buildings between 17:00 and 18:00. This can perhaps be explained by the possible high usage of the public parking buildings by motorists during this time period. For the rest of time during the day, the vehicle fire frequency in private parking buildings was generally higher than that in public parking buildings.

3.9 Heat Sources Involved in Vehicle Fires in Parking Buildings

The heat sources of vehicle fires in parking buildings can be divided into the following six groups: Short Circuit Arc; Match, Lighter & Cigarettes; Exposure Fire; Hot Object; Flame; and Not Recorded. Figure 3-9 shows the above groups of heat sources, for vehicle fires in New Zealand parking buildings from 1995 to 2003.

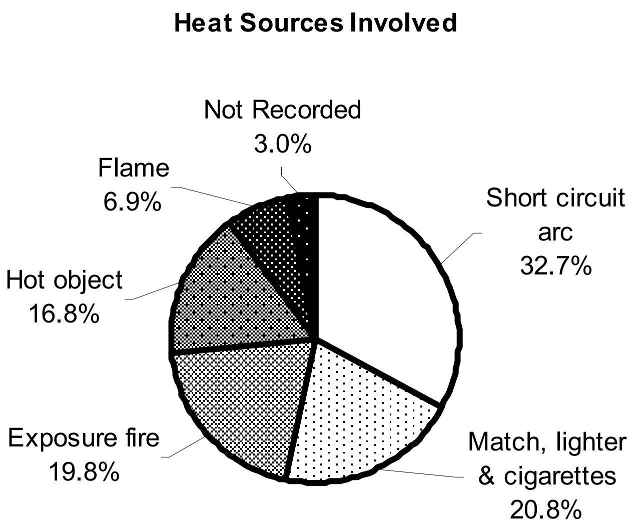


Figure 3-9: Heat sources involved in vehicles fires in parking buildings, 1995 – 2003 (From Table A – 9, Appendix A)

The further breakdown of the heat sources of vehicle fires in parking buildings are described below, according to the descriptions under the Heat Source category (New Zealand Fire Service, 1995).

Short Circuit Arc, accounting for 32.7% or 33 vehicle fires, was the leading group of heat sources involved in vehicles fires in parking buildings from 1995 to 2003. This group contained short circuit arc from unspecified causes (18.8%); mechanical damage (10.9%); defective or worn installation (2%); and water cause (1%).

The second largest group of heat sources was Match, Lighter & Cigarettes (20.8%), which can be further broken down to match (13.9%); flame type lighter (3%); possible combination of lighter, match and candle (2%); and cigarette (2%).

The first two groups of heat sources for vehicle fires in New Zealand parking buildings, ranked by number of fires, involved Short Circuit Arc; Match, Lighter & Cigarettes as discussed above. These two heat sources seem to agree with the first two fire causes of vehicle fires in New Zealand parking buildings, which were Deliberately Lit and Electrical Faults as shown in section 3.4, although in different order.

The third group of heat sources was Exposure Fire (19.8%), which involved unable to classify (14.9%); radiated heat (4%); and conducted heat (1%).

Hot Object was the fourth group of heat sources (16.8%), which included heat from liquid fuelled equipment (5.9%); improperly operating electrical equipment (3%); smoking material (3%); friction heat and overheated tyres (2%); not classified above (2%); and properly operating electrical equipment (1%).

The last two groups of heat sources involved were Flame (6.9%) and Not Recorded (3%). The group of flame involved flame escaping from liquid fuelled equipment and backfire (3%); coal or coke fuelled equipment (1%); gas or liquid powered cutting torch (1%); flame from gas equipment other than a torch (1%); and unclassified outside fire (1%).

3.10 Object First Ignited in Vehicle Fires in Parking Buildings

The objects first ignited in vehicle fires in parking buildings can be divided into the following six groups: Unknown; Electrical Components; Flammable Liquid and Gases (not aerosols or propellants); Others; Upholstery and Soft Goods; and Structure Components. Figure 3-10 illustrates these six groups of objects first ignited, for vehicle fires in New Zealand parking buildings from 1995 to 2003.

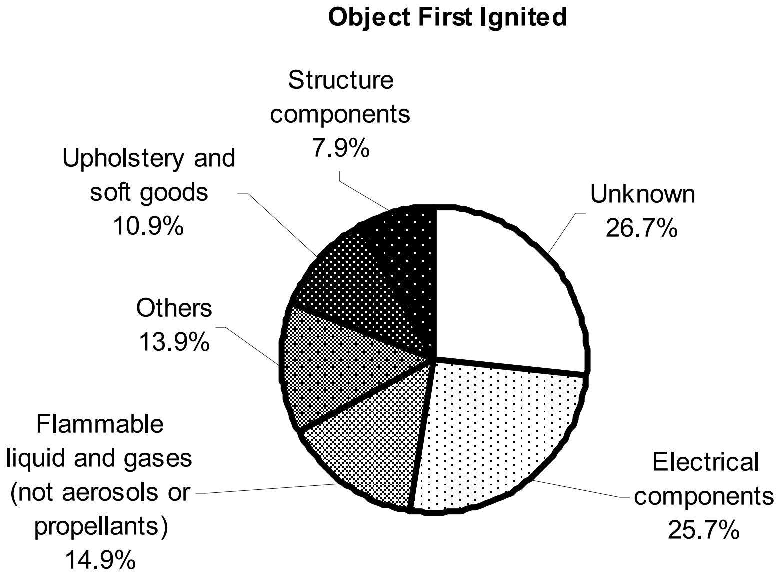


Figure 3-10: Object first ignited in vehicles fires in parking buildings, 1995 – 2003 (From Table A – 10, Appendix A)

The further analysis of objects first ignited in vehicle fires in parking buildings is explained below, in accordance with the descriptions under the category of Object Ignited (New Zealand Fire Service, 1995).

Unknown accounted for 26.7% or 27 fire incidents and was the largest group of object first ignited in vehicle fires in parking buildings from 1995 to 2003.

The next largest group of object first ignited were Electrical Components (25.7%), which can be further broken down to electrical wire and wiring insulation (22.8%);

power transfer and electrical equipment - not classified above (2%); and electronic componentry (1%).

The Flammable Liquid and Gases (not aerosols or propellants) group accounted for 14.9% of vehicle fires in parking buildings. This was followed by Others group, which can be further broken down to multiple items (5%); rubbish, garbage and waste (2%); luggage (1%); newspaper, magazine and files (1%); paper excluding newspaper or rolled paper (1%); tarpaulin, Tent, Marquee (1%); pyrotechnics, explosives and fireworks (1%); propellant, aerosol and hairspray (1%); and tyre (1%).

The Upholstery and Soft Goods group formed 10.9% and involved upholstered chairs, sofas, beds and vehicle seats (5%); clothing not being worn (2%); non made up goods including fabrics and yarn (2%); un-upholstered chairs, sofas, beds and vehicle seats (1%); and bedding (1%).

The Structure Components group accounted for 7.9% and included thermal insulation (4%); floor coverings (1%); framing, structural member, interior walls and doors (1%); lagging (1%); and awning and canopy (1%).

3.11 Material First Ignited in Vehicle Fires in Parking Buildings

The material first ignited in vehicle fires in parking buildings can be separated into the following five groups: Unknown; PVC: Floor Tiles, Guttering, Pipes, Plastic Bags, Electrical Insulation; Upholstery and Soft Goods; Flammable Liquid; and Others. Figure 3-11 demonstrates the above groups, for vehicle fires in New Zealand parking buildings from 1995 to 2003.

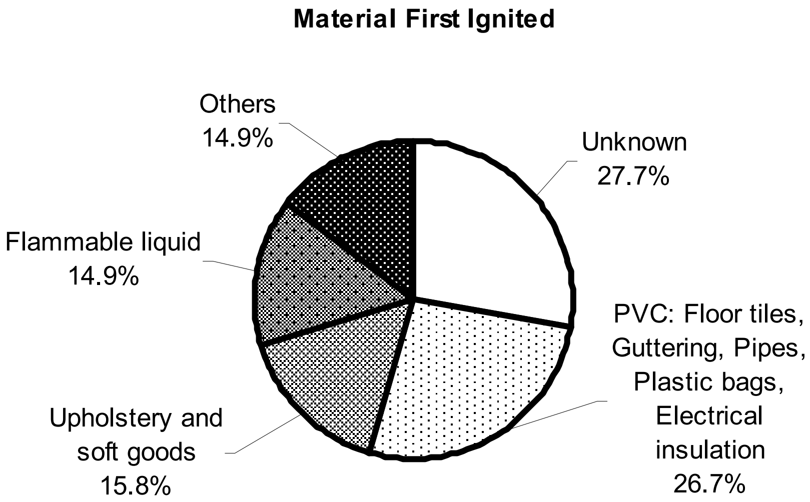


Figure 3-11: Material first ignited in vehicles fires in parking buildings, 1995 – 2003 (From Table A – 11, Appendix A)

The further breakdown of the material first ignited in vehicle fires in parking buildings are described below, according to the descriptions under the category of Type of Material Object Made of (New Zealand Fire Service, 1995).

Unknown was the largest group of material first ignited and accounted for 27.7% of all vehicle fires in parking buildings or 28 fire incidents from 1995 to 2003.

The next largest group of material first ignited was PVC (26.7%) including floor tiles, guttering, pipes, plastic bags and electrical insulation.

The Upholstery and Soft Goods group accounted for 15.8% of all fires and contained vinyl (4%); fabric and finished fibre (4%); polyurethane (3%); cotton, canvas and rayon (3%) and wool and wool mixtures (2%).

The Flammable Liquid group accounted for 14.9% of all fires and involved petrol (11.9%); flammable liquid (2%) and combustible liquid (1%).

The Others group formed 14.9% of all fires and included multiple materials first ignited (5%); rubbish (3%); rubber (2%); wood (1%); plywood (1%); treated paper (1%); waterproof canvas (1%) and oily rags (1%).

Chapter 4 Event Tree Analysis of Vehicle Fires in the Parking Building

4.1 Introduction to Event Tree Analysis

Event tree analysis is used in this chapter to analyse the vehicle fires in New Zealand parking buildings. Event tree analysis is primarily a quantitative risk assessment tool, which provides a graphical logic model for proposing an initiating event and evaluating the potential outcomes.

An event tree structure is organized by sequential events; each event generally results in two or more consequences, which are added to the tree as separate branches. The event tree can be used to identify possible outcomes following an initiating event and quantify these outcomes by assigning probabilities to each branch. The probabilities of all the branches caused by an event must add to one. The resulting probability for each outcome can therefore be obtained by multiplying the probabilities along the branches and displayed at the end of the branch.

The event tree model for vehicle fires in parking buildings in this chapter is developed to the following procedures:

- Identifying the initiating event
- Identifying the pathways to be assessed within the event tree framework; pathways are defined as those events that follow the initiating event in succession (Barry, 2002)
- Constructing the event tree branch logic
- Assigning probabilities to the initiating event and the branch of subsequent events or pathways

All the event trees for this research were built using Microsoft Excel programme (Microsoft, 2003).

4.2 Event Tree for Vehicle Fires in the Parking Building

4.2.1 Annual Vehicle Fire Frequency per Number of Vehicle Registered

As shown in section 3.2, an average of 3,371 vehicle fires occurred each year in New Zealand for eight-year period from 1995 to 2003. On average, there were approximately 2,636,579 vehicles registered each year based on the statistics in seven calendar years from 1996 to 2002, which can be found in Table B – 1 (New Zealand Registrar of Motor Vehicles, 2003), Appendix B. Thus the annual frequency of a single vehicle involved in fire in New Zealand can be obtained as:

$$3{,}371 / 2{,}636{,}579 = 1.28 \times 10^{-3} \text{ year}^{-1}$$

4.2.2 Identifying the Initiating Event and Pathways

The initiating event in this event tree is the ignition of a vehicle. This vehicle fire may happen either inside a parking building or somewhere else. There are no subsequent branches for those vehicle fires not occurring in a parking building, as this research is mainly concentrated on those vehicle fires in the parking building.

The parking building where a vehicle fire occurs can be either public or private type building. As discussed in section 3.3, a public parking building is for parking of vehicles by any member of the public and might include parking structures owned by local councils or private parking operators, covered parking belonging to shopping malls or supermarkets, etc. A private parking building is for those people who are authorised to use it and may include parking inside multi-stories office or apartment buildings, covered company fleet parking, etc.

Two types of the fire causes for vehicle fires in parking buildings are considered in the event tree model, one of which is deliberately lit fire as discussed in section 3.4.1. Another cause is accidental fire, which included all the fires not caused by deliberate or arson behaviour. Following the ignition, the fire may be confined to the vehicle first ignited or spread to one or more adjacent parked vehicles.

The pathways concerning the vehicle fires in parking buildings are therefore identified as follows:

- Fire location – in the parking building or somewhere else
- Building Type – private or public
- Fire Cause – deliberate or accidental
- Fire Spread – contained in one vehicle or spread to others
- Number of Vehicles Involved – one, two or more than three vehicles

4.2.3 Constructing the Event Tree

The constructed event tree can be seen in Figure 4-1. The annual frequency of a single vehicle involved in fire in New Zealand is 1.28×10^{-3} year^{-1} as found in section 4.2.1 and used as the frequency for the initiating event in this event tree.

There were a total of 13 branches at the end of the event tree. The resulting probability for each branch is the annual frequency of a single vehicle involved in a parking building fire, for each scenario (as defined by each branch). The value of these probabilities can be found at the end of the event tree.

The details of relevant probabilities for all pathways in this event tree are discussed in section 4.2.4.

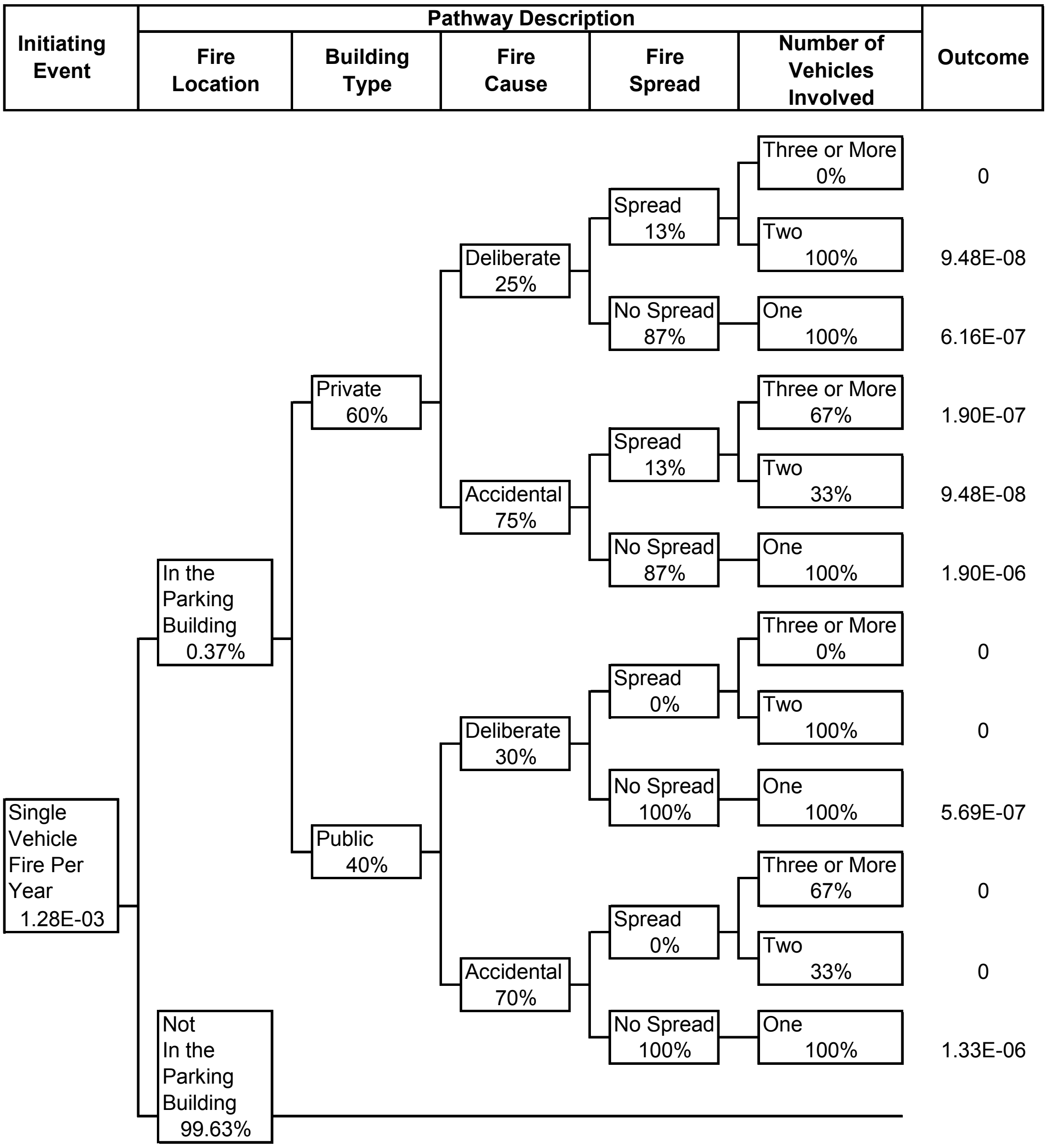


Figure 4-1: Event tree for vehicle fires in the parking building

4.2.4 Determining Probabilities

The relevant probabilities for all the pathways in event tree shown in Figure 4-1 are determined in this section. These probabilities are based on the results from the analyses of FIRS statistics for vehicle fires in New Zealand parking buildings (in Chapter 3).

Table 4-1 lists the relevant numbers of vehicles involved in parking building fires, from which the probabilities for each pathway in the event tree can be calculated.

Table 4-1: Number of vehicles involved in parking building fires for each pathway in event tree

Building Type (From section 3.3)	Fire Cause (From section 3.4)	Fire Spread (From section 3.5.1)	Number of Vehicles Involved (From section 3.5.1)		
			One Vehicle	Two Vehicles	Four Vehicles
61 (private)	15 (deliberate)	2 (spread)	-	2	0
		13 (no spread)	13	-	-
	46 (accidental)	6 (spread)	-	2	4
		40 (no spread)	40	-	-
40 (public)	12 (deliberate)	0 (spread)	-	0	0
		12 (no spread)	12	-	-
	28 (accidental)	0 (spread)	-	0	0
		28 (no spread)	28	-	-

Table 4-1 shows two incidents each involving two vehicles in the parking building fire at the same time and one incident involving four vehicles simultaneously.

4.2.4.1 Fire Location

The average number of vehicles involved in parking building fires each year was 12.6, for eight-year period from 1995 to 2003 as mentioned in section 3.2. Hence the probability of a single vehicle involved in parking building fire each year can be calculated as:

$$12.6 / 3{,}371 = 0.37\%$$

The probability of a single vehicle involved in fire per year, not occurring in a parking building, is therefore:

$$(3{,}371-12.6) / 3{,}371 = 99.63\%$$

4.2.4.2 Building Type

Table 4-1 shows the numbers of vehicles involved in private and public parking building fires as 61 and 40 respectively. Effectively, the probabilities for the branches of Private and Public in the pathway of Building Type are 60% and 40% respectively.

4.2.4.3 Fire Causes in Private Parking Buildings

As shown in Table 4-1, there were 15 deliberately lit fires out of 61 vehicle fires in private parking buildings. Thus for private parking buildings, the probability of the branch of Deliberate in the pathway of Fire Cause is:

$$15 / 61 = 25\%$$

Hence, the probability of the branch of Accidental for private parking buildings in the same pathway is 75%.

4.2.4.4 Fire Causes in Public Parking Buildings

There were also 12 deliberately lit fires out of 40 vehicle fires in public parking buildings. Hence for public parking buildings, the probability for the branch of Deliberate in the pathway of Fire Cause is:

$$12 / 40 = 30\%$$

The probability for the branch of Accidental for public parking buildings in the pathway of Fire Cause is therefore 70%.

4.2.4.5 Fire Spread and Number of Vehicles Involved – Deliberate Fires in Private Parking Buildings

For deliberately lit fire, Table 4-1 shows two vehicles involved in the multiple vehicle fire in private parking buildings. These two vehicles actually were involved in fire at the same time in one incident. There were 15 deliberate fires in private parking buildings, hence the probability for the branch of Spread in the pathway of Fire Spread is:

$$2 / 15 = 13\%$$

The probability for the branch of No Spread in the pathway of Fire Spread is therefore 87%.

Since there was no incident where more than three vehicles were involved for this situation, the probability for the branch of Three or More (vehicles involved in fire) in the pathway of Number of Vehicles Involved is 0%. The probability for the branch of Two (vehicles involved in fire) in the pathway of Number of Vehicles Involved is 100%.

4.2.4.6 Fire Spread and Number of Vehicles Involved – Accidental Fires in Private Parking Buildings

For accidental fire, Table 4-1 shows six vehicles involved in the multiple vehicle fires in private parking buildings. There were 46 accidental fires in private parking buildings, thus the probability for the branch of Spread in the pathway of Fire Spread is:

$$6 / 46 = 13\ \%$$

The probability for the branch of No Spread in the pathway of Fire Spread is therefore 87%.

From Table 4-1, there was one incident where two vehicles were involved simultaneously and another incident where four vehicles were involved concurrently. Hence the probability for the branch of Three or More (vehicles involved in fire) in the pathway of Number of Vehicles Involved can be obtained as:

4 / 6 = 67 %

The probability for the branch of Two (vehicles involved in fire) in the pathway of Number of Vehicles Involved is therefore 33%.

4.2.4.7 Fire Spread and Number of Vehicles Involved in Public Parking Buildings

Table 4-1 indicates that there were no recorded multiple vehicle fires in public parking buildings. The probability for the branch of Spread in the pathway of Fire Spread in public parking buildings is 0%, for both deliberate and accidental fire causes. The probability for the branch of No Spread in the pathway of Fire Spread is therefore 100% for both fire causes in public buildings.

In Figure 4-1, the pathway for Number of Vehicles Involved is still constructed for completeness and the relevant probabilities for private parking building are applied.

4.3 Event Tree for Vehicle Fires in Non-Sprinklered Parking Building

4.3.1 Vehicle Fire Frequency per Vehicle Visit

4.3.1.1 The Definition

The fire frequency for each branch of event tree in Figure 4-1 was based on the total number of vehicles involved in parking building fires and registered vehicles in New Zealand. It indicates the annual frequency of one vehicle involved in fire in the parking building for the scenario defined by each branch in the event tree.

For the purpose of fire risk assessment of vehicle fires in parking building, one would relate the fire frequency to the number of the actual fire incidents instead of the number of vehicles involved in fire. This consideration can include the effect of possible fire spread between vehicles and consequently more severe building damage than the single vehicle fire. The primary purpose of the parking building is for the temporary storage of vehicles. So the number of vehicle visit to the parking building would significantly affect the fire frequency, based on the assumption that the ignition probability by each vehicle visiting the parking building is the same. Chandler and Shipp (1995) also suggested that the occurrence of a vehicle fire is not time related if the vehicle engine has been on or off for more than 20 minutes (see section 2.5.1.1). It is therefore appropriate to also relate the fire frequency to the number of vehicle visit to the parking building.

An event tree is therefore introduced later in this chapter for a non-sprinklered parking building, with fire frequency based on the total number of fire incidents and vehicle visits in New Zealand parking buildings.

4.3.1.2 Estimation of the Number of Total Parking Spaces in New Zealand Parking Buildings

A survey on members of the New Zealand Parking Association was carried out for this research to obtain the fire safety record and the total number of the parking buildings in New Zealand. The results were not complete due to the inadequate responses. A summary of results for number of parking buildings in New Zealand can be found in Table B – 2, Appendix B.

As part of this survey, the total number of parking spaces in two New Zealand cities was also investigated. Table 4-2 shows the number of parking spaces in parking buildings in Auckland city (J. Cotter, *pers. Comm.*) and Christchurch city (Christchurch City Council, 2003) in New Zealand.

Table 4-2: Number of parking spaces in parking buildings and registered vehicles in Auckland and Christchurch, New Zealand

City	Local council	Privately owned or operated	Private non-residential	Private residential apartment	Total in parking buildings	Total registered vehicles
Auckland	5000	12,910	24,670	3,170	45,750	725,000
Christchurch	-	-	-	-	27,000	352,068

For figures of parking spaces for Auckland city in Table 4-2, the parking spaces in private non residential parking buildings included those in shopping malls, supermarkets, and office buildings etc. The total number of registered vehicles in Auckland was for the year of 2003 (Auckland Regional Council, 2003).

The figure of parking spaces for Christchurch city shown in Table 4-2 was for all the off street bays in central Christchurch and was assumed being representative of the total parking spaces in parking buildings of whole Christchurch city. The total number of registered vehicles in Christchurch was for the year of 2002 (Christchurch City Council, 2003).

The number of parking spaces in parking buildings and registered vehicles for both cities were then used to predict the total number of parking spaces in New Zealand, based on the number of vehicles registered in New Zealand. As shown in Table B – 1 (New Zealand Registrar of Motor Vehicles, 2003) in Appendix B, there were a total of 2,841,301 vehicles registered in New Zealand in 2002. The total number of parking spaces in New Zealand parking buildings was thus estimated as:

From Auckland figure	$(2{,}841{,}301 / 725{,}000) \times 45{,}750 = 179{,}296$
From Christchurch figure	$(2{,}841{,}301 / 352{,}068) \times 27{,}000 = 217{,}899$

The results derived from the number of parking spaces and registered vehicles for both cities were reasonably close. The average value from both results was approximately 200,000 spaces and used for the determination of vehicle fire frequency in parking buildings in New Zealand.

4.3.1.3 Annual Usage Ratio of a Parking Building

For the purpose of fire risk assessment of vehicle fires in the parking building, the concept of annual usage ratio is proposed in this research. It is defined as annual vehicle visits to a particular parking building divided by total number of parking spaces in this parking building. This represents the annual vehicle turnover rate in a particular parking building; the annual usage ratio also expresses the annual average number of vehicle visits to one parking space in the building. The parking building operators in New Zealand generally keep the yearly record of total vehicle visits into their parking buildings.

The number of car parking visits to Christchurch City Council's parking buildings was 1,115,000 a year in 2003 (Christchurch City Council, 2003). The number of the parking bays in these buildings was 3,164 (K. Scott, *pers. Comm.*), therefore the average annual usage ratio or turnover ratio is:

$$1{,}115{,}000 \text{ visit year}^{-1} / 3{,}164 \text{ (space)} \approx 350 \text{ visit/year}$$

4.3.1.4 Estimation of Total Vehicle Visits to New Zealand Parking Buildings and Fire Frequency

Based on the estimation of 200,000 parking spaces in New Zealand parking buildings, the total annual vehicle visits to New Zealand parking buildings can be obtained as:

$$200{,}000 \text{ (spaces)} \times 350 \text{ visit/year} = 70{,}000{,}000 \text{ visit/year or visit year}^{-1}$$

As presented in section 3.2, the actual number of fire incidents involving vehicles in New Zealand parking buildings from 1995 to 2003 was 96. The average number of fire incidents in New Zealand parking buildings where vehicles were involved was 12 each year. The frequency of vehicle fires in the parking building for each vehicle visit is thus:

$$12 \text{ year}^{-1} / 70{,}000{,}000 \text{ visit year}^{-1} = 1.71 \times 10^{-7} \text{ visit}^{-1}$$

4.3.2 Identifying the Initiating Event and Pathways

The initiating event in this event tree is the ignition of a vehicle fire in the non-sprinklered parking building. The pathways for the vehicle fires in the non-sprinklered parking buildings are identified as follows:

- Building Type – private or public
- Fire Cause – deliberate or accidental
- Fire Spread – contained in one vehicle or spread to others
- Number of Vehicles Involved – one, two or more than three vehicles

The background and description of these pathways can be found in section 4.2.1.

4.3.3 Constructing the Event Tree – Non-Sprinklered Parking Building

The vehicle fire frequency of 1.71×10^{-7} visit^{-1}, as found in section 4.3.1.4, was used for the initiating event in the event tree for vehicle fires in a non-sprinklered parking building. The completed event tree is shown in Figure 4-2.

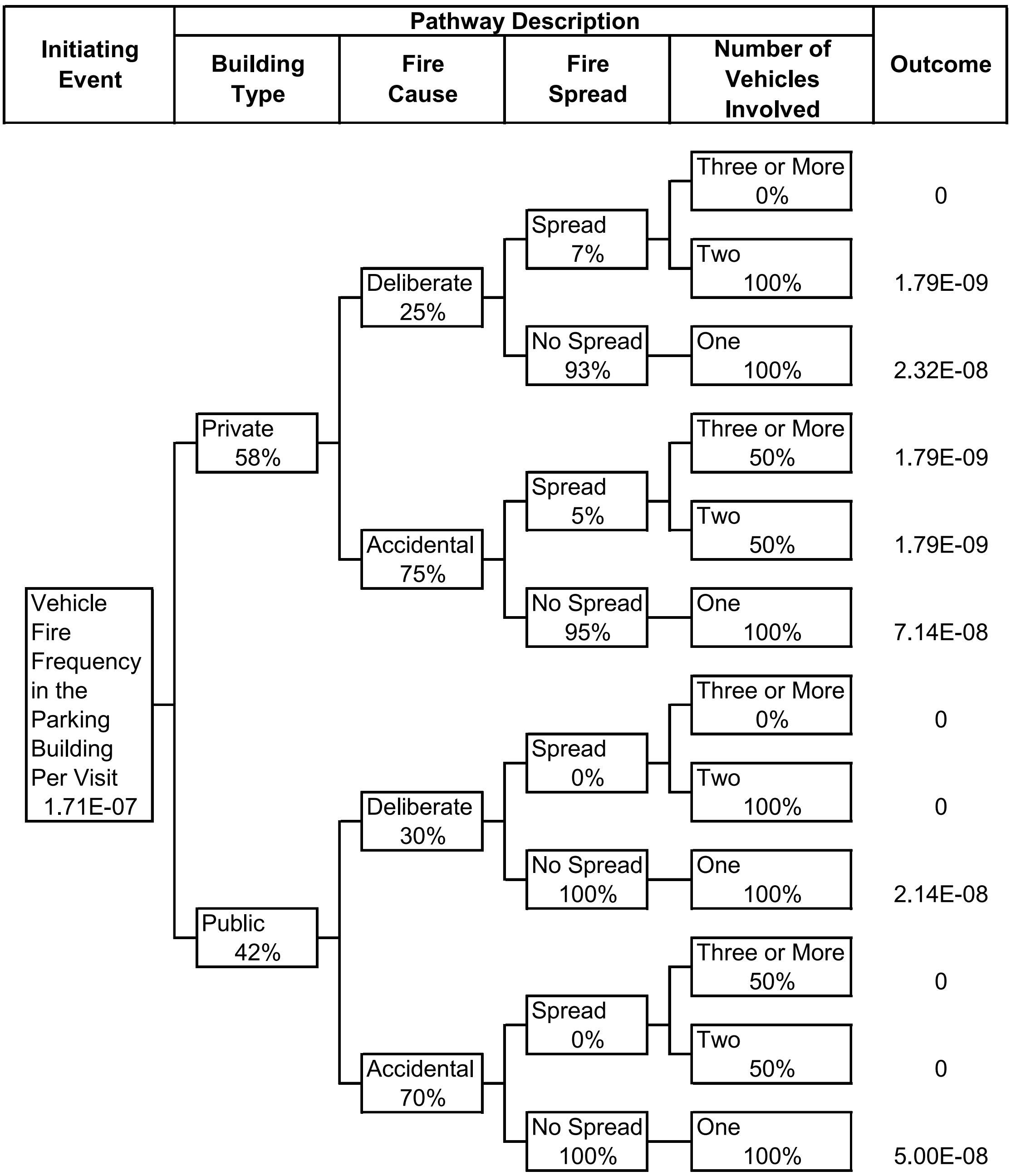


Figure 4-2: Event tree for vehicle fire incidents in non-sprinklered parking building

There were a total of 12 branches at the end of this event tree. The consequential probability is the vehicle fire frequency per each vehicle visit in any non-sprinklered parking building, for each scenario as defined by each branch. These frequencies are shown at the end of the event tree.

The details of relevant probabilities for all pathways in this event tree are described in section 4.3.4.

4.3.4 Determining Probabilities

The relevant probabilities for all pathways in the event tree as shown in Figure 4-2 are determined in this section. Table 4-3 listed the actual number of vehicle fire incidents in New Zealand parking buildings for each pathway, from which the relevant probabilities in the event tree can be calculated. These fire occurrences were obtained from Table 4-1 by considering those vehicle fires where multiple vehicles were involved in one incident. It should be noted that the fire occurrences in public buildings match those in Table 4-1 because fire spreads only occurred in the private buildings.

Table 4-3: Number of vehicle fire incidents in parking buildings for each pathway in event tree

Building Type (From section 3.3)	Fire Cause (From section 3.4)	Fire Spread (From section 3.5.1)	Number of Vehicles Involved (From section 3.5.1)		
			One Vehicle	Two Vehicles	Four Vehicles
56 (private)	14 (deliberate)	1 (spread)	-	1	0
		13 (no spread)	13	-	-
	42 (accidental)	2 (spread)	-	1	1
		40 (no spread)	40	-	-
40 (public)	12 (deliberate)	0 (spread)	-	0	0
		12 (no spread)	12	-	-
	28 (accidental)	0 (spread)	-	0	0
		28 (no spread)	28	-	-

The data in Table 4-3 were based on New Zealand Fire Service FIRS statistics. The performance of the fire protection system such as sprinklers was not available in the statistical data as discussed in section 3.1.4. It was assumed that the effect of sprinklers on the fire occurrences in Table 4-3 can be ignored. Hence the derived probabilities in the event tree in Figure 4-2 are considered for the situation of non-sprinklered parking building.

4.3.4.1 Building Type

Table 4-3 shows the vehicle fire occurrences in private buildings as 56; the probability for the branch of Private in the pathway of Building Type is therefore:

$$56 / 96 = 58\%$$

The probability for the branch of Public in the pathway of Building Type is hence 42%.

4.3.4.2 Fire Causes in Private Parking Buildings

Table 4-3 shows 14 deliberately lit fires out of 56 vehicle fires in private parking buildings. Hence for private parking buildings, the probability of the branch of Deliberate in the pathway of Fire Cause is:

$$14 / 56 = 25\%$$

The probability of the branch of Accidental for private parking buildings in the same pathway is therefore 75%.

4.3.4.3 Fire Causes in Public Parking Buildings

As obtained in section 4.2.4.4, the probability for the branches of Deliberate and Accidental for public parking buildings in the pathway of Fire Cause is 30% and 70% respectively.

4.3.4.4 Fire Spread and Number of Vehicles Involved – Deliberate Fires in Private Parking Buildings

There was only one deliberately lit incident involving two vehicles in private parking buildings as shown in Table 4-3. There were 14 deliberate fire incidents in private parking buildings, hence the probability for the branch of Spread in the pathway of Fire Spread is:

$$1 / 14 = 7\%$$

The probability for the branch of No Spread in the pathway of Fire Spread is therefore 93%.

The probability for the branch of Three or More (vehicles involved in fire) in the pathway of Number of Vehicles Involved is 0%, as there was no incident where more than three vehicles were involved for this situation. The probability for the branch of Two (vehicles involved in fire) in the pathway of Number of Vehicles Involved is then 100%.

4.3.4.5 Fire Spread and Number of Vehicles Involved – Accidental Fires in Private Parking Buildings

There were two accidental fire incidents involving multiple vehicles in private parking buildings as shown in Table 4-3. There were 42 deliberate fire incidents in private parking buildings, hence the probability for the branch of Spread in the pathway of Fire Spread is:

2 / 42 = 5%

The probability for the branch of No Spread in the pathway of Fire Spread is therefore: 95%.

Table 4-3 shows one incident where two vehicles were involved simultaneously and another incident where four vehicles were involved at the same time. Hence the probability for the branch of Three or More (vehicles involved in fire) in the pathway of Number of Vehicles Involved can be obtained as:

1 / 2 = 50%

The probability for the branch of Two (vehicles involved in fire) in the pathway of Number of Vehicles Involved is therefore 50%.

4.3.4.6 Fire Spread and Number of Vehicles Involved in Public Parking Buildings

As obtained in section 4.2.4.7, the probability for the branch of Spread in the pathway of Fire Spread in public parking buildings is 0%, for both deliberate and accidental fire causes. The probability for the branch of No Spread in the pathway of Fire Spread is therefore 100% for both fire causes in public buildings.

In Figure 4-2, the pathway for Number of Vehicles Involved is still constructed for completeness and the relevant probabilities for private parking building are applied.

4.4 Event Tree for Vehicle Fires in Sprinklered Parking Building

Generally, the operation of sprinklers can cool the environment, control the fire spread, thus protecting the building. For the situation in a parking structure, the various Australian fire tests reviewed in section 2.2.4 (BHP, 1987; Bennetts et al., 1990) showed that sprinkler operations can confine the fire within the test car, therefore preventing the vehicle fire from further development in the structure. This was also suggested by Schleich et al. (1999) as discussed in section 2.1.3.

Based on the above discussion, the event tree model in this research assumes that the activation of the sprinkler system in the event of a vehicle fire can constrain the fire within the originally ignited vehicle and protect the building from the fire damage. Effectively this means that there will be no vehicle fire spread in a sprinklered parking building.

The event tree for vehicle fires in sprinklered parking building was constructed from the event tree shown in Figure 4-2 for non-sprinklered parking building. The only difference is the probabilities in the pathway of Fire Spread.

Marryatt et al. (1988) found that the success rate of automatic sprinkler systems was more than 99% during 100-year period from 1886 to 1986 in Australia and New Zealand. The sprinkler system success probability was therefore assumed to be 100%. Based on this assumption, the probability for each branch of Spread in the pathway of Fire Spread is 0%. The probability for each branch of No Spread in the same pathway is therefore 100%. The constructed event tree for vehicle fires in a sprinklered parking building is shown in Figure 4-3.

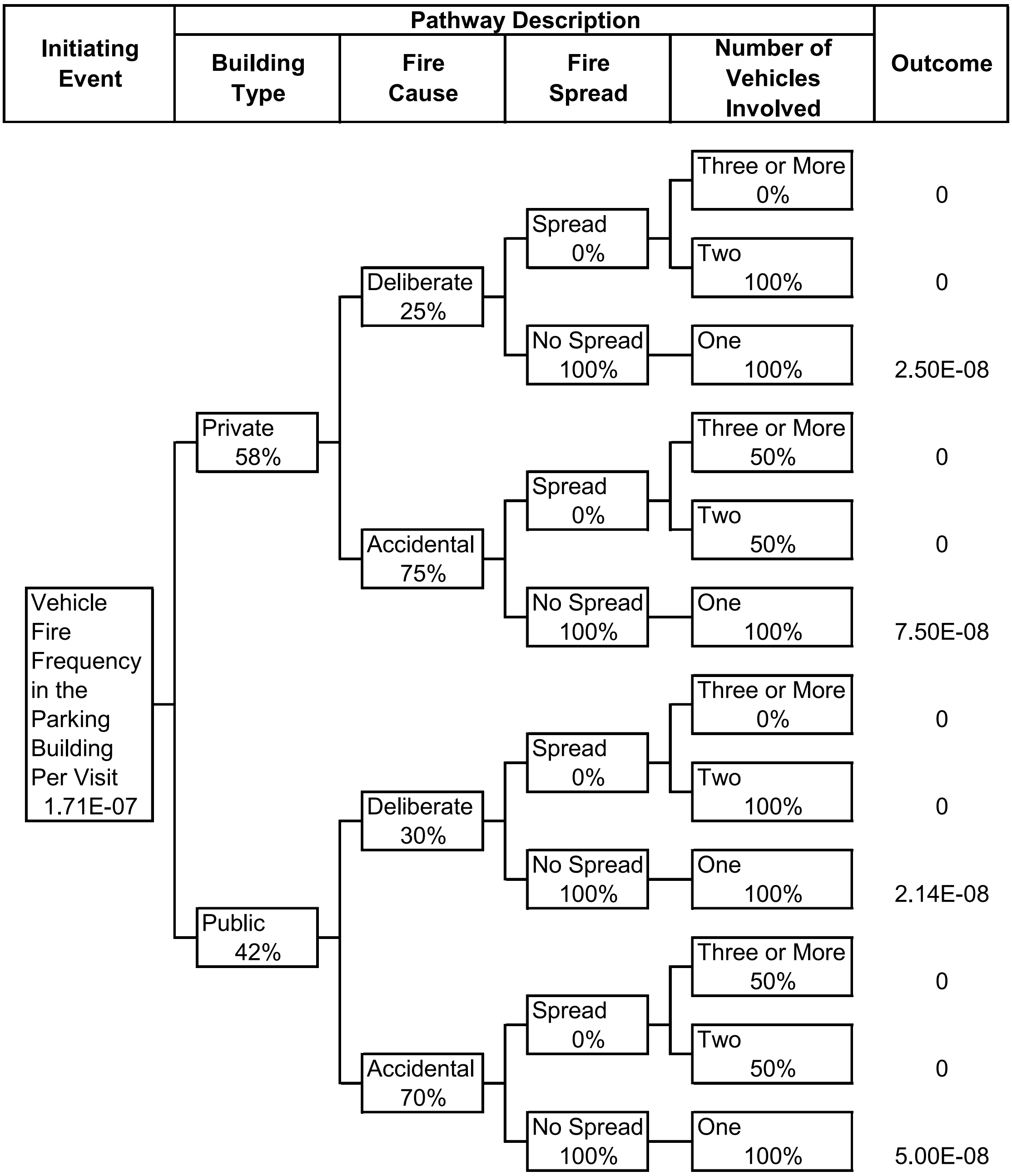


Figure 4-3: Event tree for vehicle fire incidents in sprinklered parking building

4.5 Summary of Vehicle Fire Frequencies in Parking Buildings

The vehicle fire frequency per vehicle visit for each branch in event trees was summarised in Table 4-4, for both non-sprinklered and sprinklered parking buildings.

Table 4-4: Summary of the vehicle fire frequency per visit for each branch of event trees – non-sprinklered and sprinklered parking buildings

<table>
<tr><th colspan="5">Non-Sprinklered</th></tr>
<tr><th>Building Type</th><th>Fire Cause</th><th>Fire Spread</th><th>Number of Vehicles Involved</th><th>Fire Frequency (visit^{-1})</th></tr>
<tr><td rowspan="6">Private</td><td rowspan="3">Deliberate</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>1.79×10^{-9}</td></tr>
<tr><td>No Spread</td><td>One</td><td>2.32×10^{-8}</td></tr>
<tr><td rowspan="3">Accidental</td><td rowspan="2">Spread</td><td>Three or More</td><td>1.79×10^{-9}</td></tr>
<tr><td>Two</td><td>1.79×10^{-9}</td></tr>
<tr><td>No Spread</td><td>One</td><td>7.14×10^{-8}</td></tr>
<tr><td rowspan="6">Public</td><td rowspan="3">Deliberate</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>0</td></tr>
<tr><td>No Spread</td><td>One</td><td>2.14×10^{-8}</td></tr>
<tr><td rowspan="3">Accidental</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>0</td></tr>
<tr><td>No Spread</td><td>One</td><td>5.00×10^{-8}</td></tr>
<tr><th colspan="5">Sprinklered</th></tr>
<tr><th>Building Type</th><th>Fire Cause</th><th>Fire Spread</th><th>Number of Vehicles Involved</th><th>Fire Frequency (visit^{-1})</th></tr>
<tr><td rowspan="6">Private</td><td rowspan="3">Deliberate</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>0</td></tr>
<tr><td>No Spread</td><td>One</td><td>2.50×10^{-8}</td></tr>
<tr><td rowspan="3">Accidental</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>0</td></tr>
<tr><td>No Spread</td><td>One</td><td>7.50×10^{-8}</td></tr>
<tr><td rowspan="6">Public</td><td rowspan="3">Deliberate</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>0</td></tr>
<tr><td>No Spread</td><td>One</td><td>2.14×10^{-8}</td></tr>
<tr><td rowspan="3">Accidental</td><td rowspan="2">Spread</td><td>Three or More</td><td>0</td></tr>
<tr><td>Two</td><td>0</td></tr>
<tr><td>No Spread</td><td>One</td><td>5.00×10^{-8}</td></tr>
</table>

4.6 Comparison of Annual Fire Frequencies between General and Parking Buildings

4.6.1 Fire Frequencies in General Buildings

Fire frequency in a building can be expressed by the following equation, based on a study by Ramachandran (1988):

$F = K \times A^{\alpha}$ **Equation 4-1**

where	K and α	Constants for a particular type of the building
	A	The total floor area of the building

Vrouwenvelder (1993) also described a similar method of representing the fire frequency in a building. The values for K and α for occupancies of all manufacturing industry, storage and offices are listed in Table 4-5 (Rasbash et al., 2004).

Table 4-5: Constants of K and α for various occupancies, reproduced from Rasbash et al. (2004)

Occupancy	All manufacturing industry	Storage	Offices
K	1.70×10^{-3}	6.70×10^{-4}	5.90×10^{-5}
α	0.53	0.5	0.9

4.6.2 Fire Frequencies in Parking Buildings

The vehicle fire frequency (F) in a New Zealand parking building can be given as:

$F = f \times R \times (A / P)$ **Equation 4-2**

where $f = 1.71 \times 10^{-7}$ ($visit^{-1}$)- vehicle fire frequency in the parking building per vehicle visit

R		-	annual usage ratio or turnover ratio of the parking building
A	(m^2)	-	Total area of the parking building
P = 29	(m^2/space)	-	Efficiency of parking for a parking building (Chrest et al., 2000)

The vehicle fire frequency of 1.71×10^{-7} ($visit^{-1}$) was from section 4.3.1.4. As shown in section 1.2, the number of parking spaces in a parking building can be expressed by dividing the total floor area by Efficiency. The product of annual usage ratio (R) and number of parking spaces (A / P) then yields the annual vehicle visits based on discussion in section 4.3.1.3. Finally, the product of annual vehicle visits and vehicle fire frequency per visit give the annual fire frequency in a parking building.

4.6.3 The Comparison

The annual fire frequencies for buildings of three occupancies in Table 4-5 and parking buildings are shown as a function of the total floor area, based on the results from Equation 4-1 and Equation 4-2.

The fire frequencies for parking buildings are plotted for three annual usage ratios: 350, 1,000 and 10,000. The value of 350 represents the annual usage ratio from the statistics of Christchurch City Council's parking buildings, as discussed in section 4.3.1.3.

The fire frequencies can also be expressed in Equation 4-1 term by obtaining the values of K and α for each annual usage ratio. The constant K was found to be 2.00×10^{-6} (R=350), 6.00×10^{-6} (R=1,000) and 6.00×10^{-5} (R=10,000), while constant α is 1.00 for all three annual usage ratios.

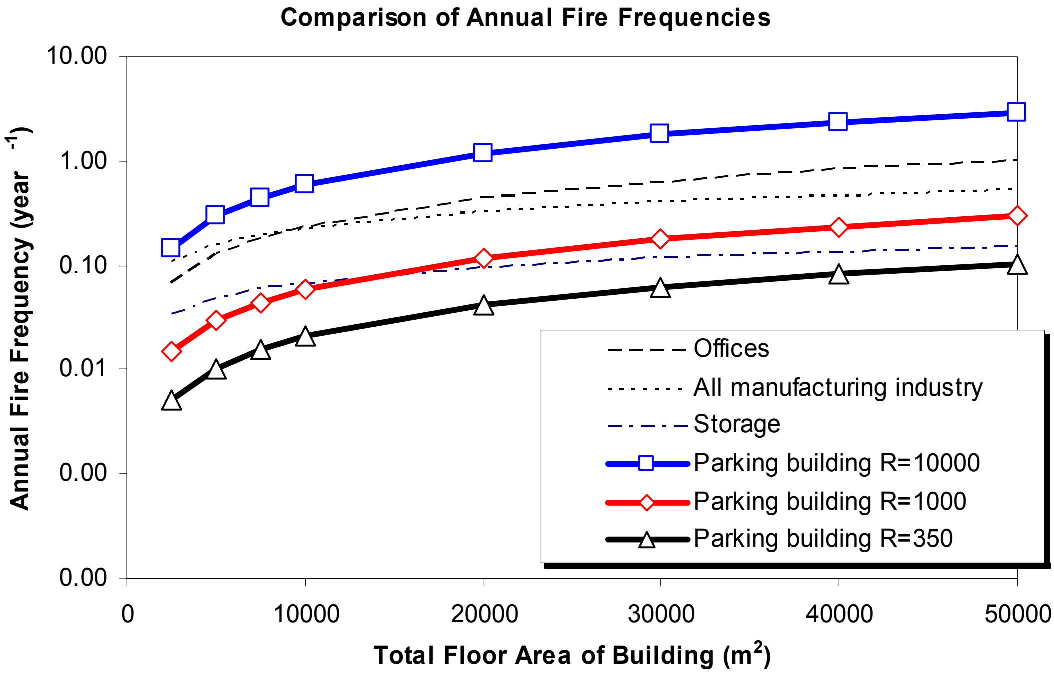


Figure 4-4: Comparison of fire frequencies between general and parking buildings

Figure 4-4 shows that the fire frequencies in the parking building are lower than those in the buildings of other occupancies when annual usage ratio is relatively low and rises with the increase of annual usage ratio.

Equation 4-2 also indicates that vehicle fire frequency in the parking building is linear to the annual usage ratio, for a particular parking building with a certain total floor area.

Chapter 5 Cost-Benefit Analysis of Sprinkler Provision in the Parking Building

5.1 General

A cost-benefit analysis (CBA) of the provision of sprinklers in New Zealand parking buildings is presented in this chapter. The analysis is from the perspective of the owner of the parking building, which can be a standalone parking building or a building with some parts dedicated for vehicle parking. The parking building is assumed to be a separate firecell, when it adjoins the structure of other occupancies. Thus the fire and smoke can be confined within the parking building without spreading to the adjacent structures and vice versa. It is also assumed that structural collapse will not occur, as demonstrated by all the vehicle fire experiments in parking structures reviewed in section 2.2.

The cost of fire damage to the structure was used for calculating the benefit of the provision of sprinklers in parking buildings. Although smoke poses a hazard to life safety in a vehicle fire, there are only two minor burn injuries each year caused by vehicle fires in New Zealand parking buildings as shown in section 3.2. In the US, Harris (1972) reported no injuries from 395 parking structure fires; while Denda (1993) found eight injuries, which were reported as not directly fire related, from over 400 parking structure fires. Therefore because of the apparent rarity of injuries, the possible resulting financial loss in parking building fires was ignored and not included in this analysis.

There was no fatality reported from 1995 to 2003 in New Zealand parking building fires as found in section 3.2. Similarly, two US studies (Harris, 1972; Denda, 1993) reviewed in section 2.5.2.1 and 2.5.2.2 indicated that there was no fatality in the parking structure fires. Consequently the financial loss from the death in parking building fires cannot be quantified and was hence not considered in this research.

There is still potential for the casualties in a parking building vehicle fire. However, this is not within the scope of this research, which is mainly concerned with the property protection.

The activation of sprinklers, in the event of a vehicle fire, can prevent the fire spread between the neighbouring vehicles and protect the building structure. Nevertheless the damage to the burning vehicle is unavoidable; because the vehicle damage would already be significant before the sprinkler activation and sprinklers cannot extinguish the fire inside vehicle as discussed in section 2.2.2. Hence, the financial loss of vehicles in the parking building fire was also not included in the analysis.

The interruption or loss of the business, following a vehicle fire in a non-sprinklered parking building, could cause the financial loss for the building owner e.g. loss of direct fee paying income. On the other hand, the provision of sprinklers in the parking building might allow the trade-off in building design and reduction of the insurance premium cost, which would contribute to the benefit of sprinklers in the parking building. However the relevant commercially sensitive data were unavailable for inclusion at the time of this research.

In this chapter, vehicle fire risks in the parking building are identified on a yearly basis for both a non-sprinklered and a sprinklered situation. The costs of installing and maintaining sprinklers in parking buildings are also described. The cost-benefit analysis of sprinklers in New Zealand parking buildings is then presented as four scenarios considered in this research. Finally a case study, including sensitivity analysis, is carried out using @Risk programme (Palisade, 2002b).

5.2 Annualised Risk of Vehicle Fires in Non-Sprinklered Parking Building

5.2.1 Definition

According to the level of the fire spread between parked vehicles or the number of vehicles involved due to a single ignition, vehicle fire risks in a non-sprinklered parking building can be classified into three fire spread scenarios, which are:

- Single vehicle involved
- Two vehicles involved
- More than three vehicles involved

In this research, the quantification of fire risks was envisaged as the product of the frequency with which a fire occurs, and the damage this fire causes. The vehicle fire risks in a non-sprinklered parking building can thus be expressed on a yearly basis as:

Annualised Risk	= ∑	Annual vehicle fire frequency for each fire spread scenario	×	Fire damage for each fire spread scenario	**Equation 5-1**
(dollar/year)		(year^{-1})		(dollar)	

For each scenario concerning the spread of fire between vehicles parked in a non-sprinklered parking building, the annual fire frequency can be obtained as:

Annual vehicle fire frequency for each fire spread scenario	=	Fire frequency per vehicle visit for each fire spread scenario	×	Total vehicle visits per year	**Equation 5-2**
(year^{-1})		(visit^{-1})		(visit/year)	

By assuming that fire damage is generally confined to the area a burning vehicle occupies, the fire damage for each scenario can be shown as:

Fire damage for each fire spread scenario (dollar)	=	Unit fire damage in non-sprinklered parking building (dollar/m^2)	×	Single parking area (m^2)	×	Number of vehicles involved in fire

Equation 5-3

where

Single parking area (m^2)	=	Parking building area (m^2)	/	Number of parking spaces

Substituting Equation 5-2 and Equation 5-3 into Equation 5-1, the total annualised vehicle fire risk (dollar/year) in a non-sprinklered parking building can be written as:

$$\text{Annualised Risk} = \sum (f \times n) \times D \times A \times R$$ **Equation 5-4**

where f (visit^{-1}) - Fire frequency in a non-sprinklered parking building per vehicle visit for each fire spread scenario

n - Number of vehicles involved in fire for each fire spread scenario

D (dollar/m^2) - Unit fire damage in a non-sprinklered parking building

A (m^2) - Total floor area of the parking building

R (visit/year) - Annual usage ratio defined as the ratio of annual vehicle visits to number of parking spaces in the parking building (see section 4.3.1.3)

The details for parameters of f, n and D in Equation 5-4 are discussed in the following sections. The values for f and n can be found in Table 5-1. The details for annual usage ratio (R) can be found in section 4.3.1.3.

5.2.2 f – Fire Frequency per Vehicle Visit for Each Fire Spread Scenario

As discussed in section 5.2.1, vehicle fire risks in a non-sprinklered parking building are classified into three fire spread scenarios as shown in Table 5-1, according to the number of vehicles involved in fire. The fire frequency per vehicle visit for each scenario is obtained from the results of event tree for vehicle fires in a non-sprinklered parking building as shown in Table 4-4, by adding up the frequencies for each fire spread scenario. These frequencies are listed separately in Table 5-1 for both private and public type parking buildings.

Table 5-1: Number of vehicles involved and vehicle fire frequencies for each fire spread scenario in non-sprinklered parking buildings

Scenario by number of vehicles involved	**Number of vehicles involved (n)**	**Fire frequency per vehicle visit (f, year^{-1}) – From Table 4-4**	
		Private parking building	Public parking building
More than three vehicles	4	1.79×10^{-9}	0
Two vehicles	2	3.57×10^{-9}	0
Single vehicle	1	9.46×10^{-8}	7.14×10^{-8}
$\sum (f \times n)$		Private	Public
		1.09×10^{-7}	7.14×10^{-8}

5.2.3 n – Number of Vehicles Involved for Each Fire Spread Scenario

As discussed in section 3.5.1, there was one incident where four vehicles were involved in a parking building fire due to single ignition. This was also the only incident involving more than three vehicles in New Zealand parking building fires from 1995 to 2003. Thus for the scenario of more than three vehicles involved in a fire, the number of vehicles involved (n) in Equation 5-4 is four.

According to the fire spread scenarios discussed in section 5.2.1, there are three values for the number of vehicles involved (n), which are 1, 2 and 4. These values are also shown in Table 5-1.

5.2.4 D – Unit Fire Damage in Non-Sprinklered Parking Buildings

5.2.4.1 Fitted Distribution from Historical Data

At the time of this research, information in financial terms regarding the damage caused by vehicle fires was not found for New Zealand parking buildings. The fire damages reported by a 1972 US study (Harris, 1972) reviewed in section 2.5.2.1 of this report, were used to determine the unit fire damage (D) in non-sprinklered parking buildings. The unit fire damage is the fire damage to the structure caused by vehicle fires and it is expressed in monetary value per unit area.

This US study surveyed 1,686 automobile parking structures with a total of 778,000 parking spaces in the United States and Canada. There were 395 fires reported during the entire life span of these structures. It was reported that 27 fires caused damage to the building and 368 fires resulted in damage confined to the vehicle.

In 27 fires causing damage to building, the losses were recorded for 16 fires in US dollars; the remaining 11 fires were reported causing damages fewer than $5,000 USD dollars without further details. It was assumed in this research that each of these fires resulted in a loss of $2,500 USD.

For 368 fires which caused no damage to the building according to the 1972 US study, it was assumed in this research that these fires still caused some minor damages to the building. The financial loss of $100 USD was assumed for each of these fires.

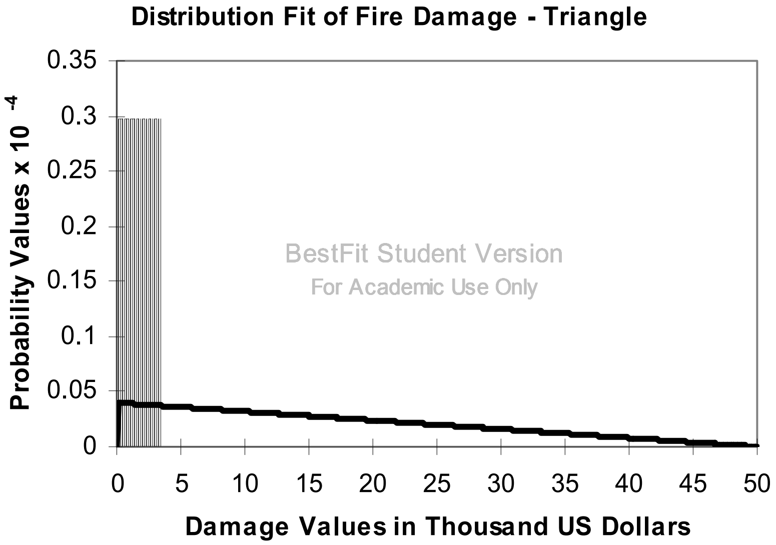
The damage details for all 395 fires from the 1972 US study are shown in Table 5-2 in 1972 US dollars.

Table 5-2: Vehicle fire damages in parking buildings in 1972 US dollars, reproduced from Harris (1972)

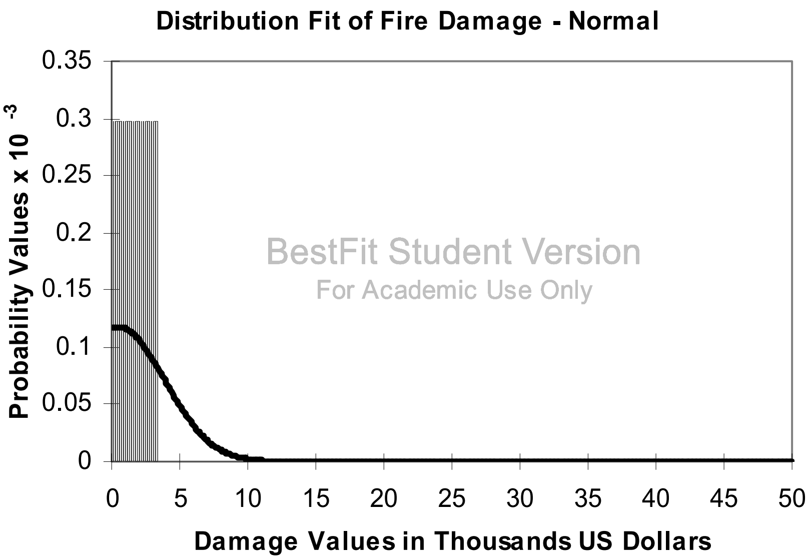
Damage in US dollars	Value used in BESTFIT	Number of fires
$50,000	$50,000 (maximum)	1
$40,000	$40,000	1
$18,400	$18,400	1
$9,000	$9,000	1
$4,000 – 4,999	$4,500	1
$1,000 – 1,999	$1,500	4
$500 – 999	$750	2
Under $500	$500	5
Under $5,000; No details	$2,500	11
Total number of incidents with damage		27
No damage reported	$100 (minimum)	368
Total number of incidents		395

The “BestFit” programme (Palisade, 2002a) was used to find the appropriate distribution fitting these data in Table 5-2. “BestFit” is a programme that fits statistical distributions to input data and displays the results in graph and table forms.

Two distributions, as shown in Figure 5-1, were found to reasonably fit the financial loss data of vehicle fire damage from Table 5-2. One fit was a triangle distribution with a mean of $16,779; the goodness-of-fit test was by Chi-Square method. Another fit was a normal distribution with a mean of $497; the goodness-of-fit test was by Kolmogorov-Smirinov method. The statistical details of these two fit results can be found in Table C – 2, Appendix C.



Fit by triangle distribution with a mean of $16,779



Fit by normal distribution with a mean of $497

Figure 5-1: Fitted distributions for vehicle fire damages in parking buildings in 1972 US dollars

There was a significant difference in mean value between these two distributions. To achieve a more conservative result, the mean value of $16,779 USD from the triangle distribution was used to derive the unit fire damage in non-sprinklered parking buildings in New Zealand. It was also assumed that this value represents the loss from the damage confined in the parking area by a single vehicle. This assumption would yield a relatively conservative value of unit fire damage, because the 1972 US study included some multiple vehicles fires.

5.2.4.2 Estimation of Unit Fire Damage in New Zealand Parking Buildings

The loss of $16,779 USD represents the expected value of property damage caused by single vehicle fire in parking buildings in 1972 in the US. This figure needs to be inflated to the current monetary value before it can be converted to New Zealand currency to obtain the unit fire damage in New Zealand situation. The American Producer Price Index (PPI) was used to inflate this figure (E. Crampton, *pers. Comm.*). The trend of American PPI for industrial commodity from 1972 to 2003 is shown in Figure 5-2 (U.S. Department of Labor, 2004); the relevant data can also be found in Table C – 1, Appendix C.

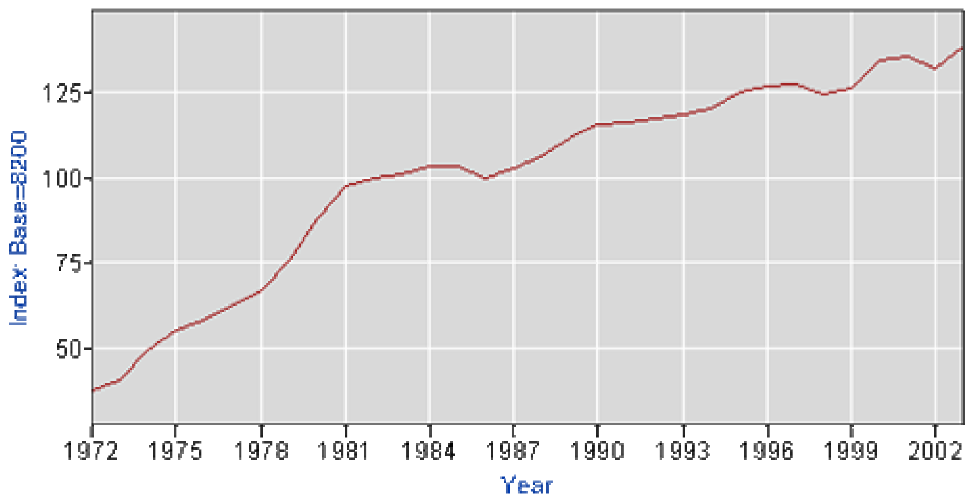


Figure 5-2: The trend of American Producer Price Index for industrial commodity from 1972 to 2003, reproduced from U.S. Department of Labor (2004)

The American PPI of industrial commodity for 1972 and 2003 were 37.8 and 139.1 respectively. For single vehicle parking area, the property damage caused by vehicle fire can therefore be obtained in 2003 US dollars as:

$$\$16{,}779 \text{ USD} \times (139.1 / 37.8) = \$61{,}700 \text{ USD}$$

Using an Efficiency value of 29 m^2 per space in the parking building as discussed in section 4.6.2, the unit fire damage by vehicle fire in a non-sprinklered parking building in US can be determined as:

$$\$61{,}700 \text{ USD} / 29 \text{ m}^2 = \$2{,}129 \text{ USD/m}^2$$

In 2003, the exchange rate between US dollar and New Zealand dollar (NZD) was approximately 0.55 USD/NZD (The Treasury, 2004), therefore the unit fire damage by vehicle fire in the parking building in 2003 New Zealand dollars is:

$$\$2{,}129 \text{ USD} / 0.55 = \$3{,}871 \text{ NZD/m}^2$$

This value was used to represent the unit fire damage (D) in Equation 5-4 in this analysis. As discussed in section 1.3, a property damage of $75,000 Australian dollars was reported for a fire incident involving three vehicles, in a non-sprinklered and closed car park (James, 2003). The exchange rate between Australian and New Zealand dollar was approximately 0.9 AUD/NZD in 2003 (The Treasury, 2004). Based on an Efficiency value of 29m^2 per space, a unit fire damage of 958 NZD/m^2 can be derived from this Australian incident. This value seems to indicate that the unit fire damage value (3,871 NZ dollars/m^2) used in this analysis is in the reasonable magnitude, although it is higher than the value derived from the Australian vehicle fire incident.

5.3 Reduced Annualised Risk of Vehicle Fires in Sprinklered Parking Building

5.3.1 Definition

Sprinklers can prevent the spread of fire between vehicles as discussed in section 4.4. Hence, there is only one fire spread scenario where a single vehicle is involved in fire for a sprinklered parking building.

The reduced annualised risk (dollar/year) in a sprinklered parking building can be derived in a similar manner as that in a non-sprinklered situation and expressed as:

Reduced Annualised Risk = $f_s \times (p \times D) \times A \times R$ **Equation 5-5**

where f_s ($visit^{-1}$) - Vehicle fire frequency in sprinklered parking building per vehicle visit

p (%) - Reduction percentage to allow reduced fire damage in sprinklered parking building

The parameters of f_s and p are discussed in the following sections; the meanings of parameters D, A and R are same as those for a non-sprinklered parking building described in section 5.2.

5.3.2 f_s – Fire frequency in Sprinklered Situation

The fire frequency, for both private and public sprinklered parking buildings, is based on the results of event tree for vehicle fires in sprinklered parking building from Table 4-4. Similar to the non-sprinklered situation, these fire frequencies were obtained by adding up the frequencies on relevant branches for both private and public parking buildings, and listed in Table 5-3.

Table 5-3: Vehicle fire frequencies in sprinklered parking buildings

Scenario by number of vehicles involved	**Frequency per vehicle visit (f_s, $year^{-1}$) – From Table 4-4**	
	Private parking building	Public parking building
Single vehicle	1.00×10^{-7}	7.14×10^{-8}

For public parking buildings, the frequency in a sprinklered parking building is actually equal to the value of $\sum (f \times n)$ for a non-sprinklered parking building from Table 5-1, because there is no vehicle fire spread in New Zealand public parking buildings.

5.3.3 p – Reduction Percentage to Allow Reduced Fire Damage

The vehicle fire controlled by sprinklers can still result in certain damage to the sprinkler protected parking building, which can be expressed as a percentage (p) of the unit fire damage to a non-sprinklered parking building.

For a wide range of occupancies in the US, the average fire loss in a non-sprinklered building is approximately 4.5 times higher than that in an adequately sprinklered building (Rasbash et al., 2004). Based on this value, the ratio between the fire loss in the sprinklered and non-sprinklered buildings is about 0.18. The damage to those vehicles involved in the parking building fire is not considered in the cost-benefit analysis in this research, so a lower value of reduction percentage would be appropriate. A value of 15% was assumed for p in this research.

5.4 Cost of Automatic Sprinkler System in New Zealand Parking Buildings

5.4.1 General

The costs for installing and maintaining sprinkler systems in New Zealand parking buildings are presented in this section (C. Mak, *pers. Comm.*). These costs were the figures at the time of the research and in New Zealand dollars.

Two cost types are given, fixed and marginal. In particular, the fixed cost depends on the availability of the existing sprinkler system in a parking building. When a parking building is part of the building already protected by sprinklers, the fixed costs for installation and maintenance is generally zero.

The sprinkler costs were therefore categorised to the availability of extending from an existing sprinkler system. The category of Available would include the sprinkler system for parking building in or adjoining a building already protected by sprinklers; whereas the category of Not Available would involve the system for a standalone parking building.

5.4.2 Annual Maintenance Cost

The annual maintenance costs for sprinkler system in the parking building are generally composed of fixed and marginal costs for inspection of the sprinkler system. The fixed cost includes the monthly testing and biennial inspection of the sprinkler system. Table 5-4 summarises both costs according to the availability of extending from an existing sprinkler system.

Table 5-4: Annual maintenance cost of the sprinkler system in parking buildings

Extending from an existing sprinklers	**Annual maintenance cost**	
	Fixed M_F - dollar/year	Marginal M_m - dollar/(m^2year)
Available	0	0.025
Not Available	750	0.025

Therefore the annual maintenance costs of sprinklers can be obtained based on the availability of an existing system.

For extension from an existing sprinkler system Available, the annual maintenance cost of sprinkler system (dollar/year) in the parking building is:

$$\text{Annual Maintenance Cost} = M_m \times A \qquad \textbf{Equation 5-6}$$

For extension from an existing sprinkler system Not Available, the annual maintenance cost of sprinkler system (dollar/year) in the parking building is:

$$\text{Annual Maintenance Cost} = M_F + M_m \times A \qquad \textbf{Equation 5-7}$$

where	A (m^2)	-	Total floor area of the parking building
	M_F (dollar/year)	-	Annual fixed maintenance cost
	M_m (dollar/(m^2year))	-	Annual marginal maintenance cost per unit floor area

5.4.3 Initial Cost

The initial sprinkler costs for sprinkler system in the parking building generally consist of a fixed cost for water supply to the system and a marginal cost for installing sprinklers. These are shown in Table 5-5 according to the availability of extending from an existing sprinkler system, similar to annual maintenance cost.

Table 5-5: Initial cost of the sprinkler system in parking buildings

Extending from an existing sprinklers	**Initial cost**	
	Fixed I_F - dollar	Marginal I_m - dollar/m^2
Available	0	12
Not available	20,000	12

The fixed initial cost involved the expense for water supply and did not include the expense for pump, which is generally not required in parking building situation due to the relatively low flow rate demand by the system. The initial marginal cost was based on the normal sprinkler heads, with a maximum spacing of 12 m^2 per head.

Hence initial costs of sprinklers can be obtained based on the availability of an existing system as follows.

For extension from an existing sprinkler system Available, the initial cost of sprinkler system in the parking building (dollar) is:

$$\text{Initial Cost} = I_m \times A$$ **Equation 5-8**

For extension from an existing sprinkler system Not Available, the initial cost of sprinkler system in the parking building (dollar) is:

$$\text{Initial Cost} = I_F + I_m \times A$$ **Equation 5-9**

where A (m^2) - Total floor area of the parking building

I_F (dollar) - Fixed initial cost

I_m (dollar/m^2) - Marginal initial cost per unit floor area

5.5 Analysis by Cost-Benefit Ratio Method

5.5.1 The Approach

The concept of cost-benefit analysis for the sprinkler system in a parking building is to determine what the financial advantage would have been, if the cost for installation of the sprinkler system had been put into a comparatively risky investment. This financial advantage can then be compared with the benefit gained from the installation of the sprinkler system in a parking building.

This benefit from sprinklers is represented by the annual avoidance of cost that could have incurred due to vehicle fires in a non-sprinklered parking building, had sprinklers not been installed. The cost for sprinklers is identified as the initial cost for installation of sprinkler system described in section 5.4.3.

The criterion of cost-benefit ratio is commonly used for the comparison of the alternative investment projects. This measure was also used for the cost-benefit analysis of provision of sprinklers in New Zealand parking buildings in this research. With this method, the financial equivalent benefit is divided by the financial equivalent cost to yield cost-benefit ratio.

The financial equivalent benefit is the present worth of the annual cost avoidance of fire damage by installing the sprinkler system. This present worth is expressed as the product of annual cost avoidance and the series present worth factor, which converts the annual cost avoidance to present worth based on a certain discount rate. The financial equivalent cost is the initial cost of the sprinkler system installation. The cost-benefit ratio, denoted as B/C, can then be expressed as (Barry, 2002):

$$\text{B/C} = \frac{\text{Annual Cost Avoidance} \times \text{Series Present Worth Factor}}{\text{Initial Cost}} \qquad \textbf{Equation 5-10}$$

When the cost-benefit ratio (B/C) is greater than one, it indicates that the benefit is greater than the cost. Alternatively it means that an investment higher than the initial cost of sprinklers is required to achieve the return equivalent to the benefit (annual cost avoidance) from sprinklers based on a certain discount rate. Thus, the installation of the sprinkler system in a parking building is economically acceptable. Conversely, if the cost-benefit ratio is less than one, the provision of sprinklers is considered as economically unacceptable.

5.5.2 Annual Cost Avoidance

The annual cost avoidance of vehicle fire damage by sprinklers in the parking building can be written as:

Annual cost avoidance	=	Annualised risk in non-sprinklered parking building	−	Reduced annualised risk in sprinklered parking building	−	Annual maintenance cost of sprinklers
(dollar/year)		(dollar/year)		(dollar/year)		(dollar/year)

Equation 5-11

The three parameters in Equation 5-11 have been discussed in previous sections. The annualised risk and reduced annualised risk can be found in section 5.2.1 and 5.3.1 respectively, while annual maintenance cost is described in section 5.4.2.

For the sprinkler system which can be extended from an existing installation, the annual cost avoidance can be obtained, by substituting Equation 5-4, Equation 5-5 and Equation 5-6 into Equation 5-11, and expressed as:

$$\text{Annual cost avoidance} = [\,(\textstyle\sum (f \times n) - f_s \times p\,) \times D \times R - M_m\,] \times A \qquad \textbf{Equation 5-12}$$

For the sprinkler system which cannot be extended from an existing installation, the annual cost avoidance can be obtained similarly, by substituting Equation 5-4, Equation 5-5 and Equation 5-7 into Equation 5-11, and expressed as:

$$\text{Annual cost avoidance} = [\,(\textstyle\sum (f \times n) - f_s \times p\,) \times D \times R - M_m\,] \times A - M_F \qquad \textbf{Equation 5-13}$$

5.5.3 Series Present Worth Factor and Discount Rate

As given in Chapter 5-7 of *SFPE Handbook of Fire Protection Engineering* (DiNenno, 2002), the symbol (P/A, i , N) is used to describe series present worth factor, which can be expressed in the form as shown in Equation 5-14:

$$(P/A, i, N) = [\,(1 + i)^N - 1\,] / [\,i \times (1 + i)^N\,] \qquad \textbf{Equation 5-14}$$

where P/A - Present worth of the annual cost avoidance

i (%) - Discount rate

N - Number of the years considered in the analysis

Discount rate is the annual percentage rate at which the present value of a future monetary value decreases through a certain period of time. It is used to convert all costs and benefits to the net present value or present worth, so that the comparison between alternative investment options can be performed. A discount rate (i) of 10%, which is used by the New Zealand Treasury for government project (Young, 2002), was selected for the cost-benefit analysis in this research.

In this analysis, a service life of 50 years was assumed for general parking buildings in New Zealand. It was also believed that the sprinkler system would not have to be replaced during the whole life span of the building; hence the life of the sprinkler system installed in a parking building was assumed to be 50 years. The number of the years considered (N) in this cost-benefit analysis was therefore 50.

5.6 Equations

5.6.1 Four Scenarios Considered

A total of four scenarios were considered for the cost-benefit analysis of provision of sprinklers in parking buildings, according to the availability of the existing sprinkler system and the type of the parking building. Table 5-6 listed these four scenarios for cost-benefit analysis in this research.

Table 5-6: Four scenarios considered in CBA of sprinkler provision in parking buildings

Scenario No.	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Extension from existing sprinklers	Available		Not-Available	
Type of parking building	Private	Public	Private	Public

The equations of cost-benefit ratio for all the scenarios in Table 5-6 are presented in the following sections.

5.6.2 Sprinkler Extension Available – Scenario 1 (Private) and 2 (Public)

For the sprinkler system which can be extended from an existing installation, the cost-benefit ratio can be obtained by substituting the annual cost avoidance (Equation 5-12) and initial cost (Equation 5-8) into Equation 5-10 and written as:

$$B/C = \frac{(\sum (f \times n) - f_s \times p) \times D \times R - M_m}{I_m} \times (P/A, i, N) \qquad \textbf{Equation 5-15}$$

Series present worth factor is expressed by Equation 5-14. The annual fixed maintenance cost (M_F) and fixed initial cost (I_F) for sprinklers in this situation are zero and hence do not exist in the equation. The total floor area (A) is also cancelled out in the equation.

Annual usage ratio (R) is the only variable in the equation for the parking building where extension from existing sprinklers is available. The summary of all the parameters in Equation 5-15 can be found in Table 5-7 in section 5.6.4.

5.6.3 Sprinkler Extension Not Available – Scenario 3 (Private) and 4 (Public)

For the sprinkler system which cannot be extended from an existing installation, the cost-benefit ratio can be obtained by substituting the annual cost avoidance (Equation 5-13) and initial cost (Equation 5-9) into Equation 5-10 and written as:

$$B/C \quad = \quad \frac{[\,(\sum (f \times n) - f_s \times p\,) \times D \times R - M_m\,] \times A - M_F}{I_F + I_m \times A} \times (P/A, i\,, N)$$

Equation 5-16

Series present worth factor is described by Equation 5-14. Compared with Equation 5-15 for Scenario 1 and 2, this equation has three more parameters, which are annual fixed maintenance cost (M_F), Fixed initial cost (I_F) and total floor area of the parking building (A). The two variables are annual usage ratio (R) and total floor area of the parking building (A). The summary of all the parameters in Equation 5-16 is shown in Table 5-7 in section 5.6.4.

5.6.4 Summary of Inputs for Four Scenarios

All the parameters in Equation 5-15 and Equation 5-16 are summarised in Table 5-7, for all four scenarios considered in this research as described in Table 5-6.

Table 5-7: Parameter summary of four scenarios considered in CBA

Symbol	Unit	Scenarios Considered In Analysis			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Available (Equation 5-15)		Not-Available (Equation 5-16)	
		Private	Public	Private	Public
$\sum (f \times n)$	$visit^{-1}$	1.09×10^{-7}	7.14×10^{-8}	1.09×10^{-7}	7.14×10^{-8}
f_s	$visit^{-1}$	1.00×10^{-7}	7.14×10^{-8}	1.00×10^{-7}	7.14×10^{-8}
D	$dollar/m^2$	3870	3870	3870	3870
p	%	15%	15%	15%	15%
M_F	dollar/year	0	0	750	750
M_m	$dollar/(m^2 year)$	0.025	0.025	0.025	0.025
I_F	dollar	0	0	20,000	20,000
I_m	$dollar/m^2$	12	12	12	12
(P/A, i , N)	-	9.9148	9.9148	9.9148	9.9148
i	%	10%	10%	10%	10%
N	year	50	50	50	50
R	visit/year	variable	variable	variable	variable
A	m^2	-	-	variable	variable

The meaning of symbols in Table 5-7 is listed as follows:

$\sum (f \times n)$	$\sum$ (Fire frequency per vehicle visit in a non-sprinklered parking building for each fire spread scenario × Number of vehicles involved in fire)
f_s	Fire frequency per vehicle visit in a sprinklered parking building
D	Unit fire damage in a non-sprinklered parking building
p	Reduction percentage to allow reduced fire damage in a sprinklered parking building
M_F	Annual fixed maintenance cost
M_m	Annual marginal maintenance cost per unit floor area
I_F	Fixed initial cost
I_m	Marginal initial cost per unit floor area
(P/A, i , N)	Series present worth factor
i	Discount rate
N	Number of years considered in cost-benefit analysis
R	Annual usage ratio defined as annual vehicle visits divided by the

number of parking spaces in a parking building

A Total floor area of the parking building considered in the analysis

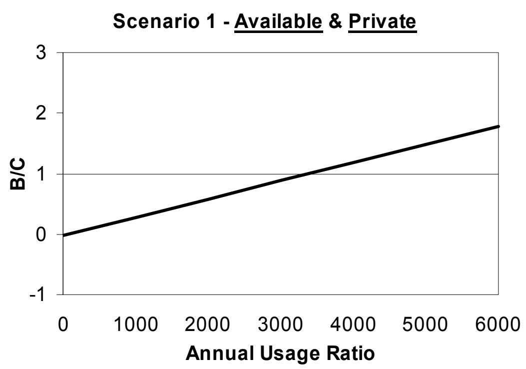
- Not applicable (see section 5.6.2)

For Scenario 1 and 2 where the extension from existing sprinklers is available, annual usage ratio (R) is the only variable in the analysis. For Scenario 3 and 4 where the extension from existing sprinklers is not available, annual usage ratio (R) and total floor area of parking building (A) are variables.

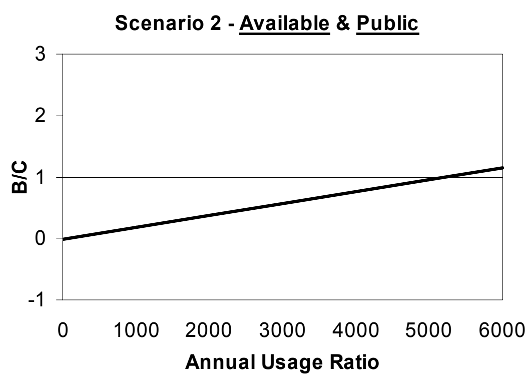
5.7 Results

5.7.1 Sprinkler Extension Available – Scenario 1 (Private) and Scenario 2 (Public)

The results from Equation 5-15 are shown in Figure 5-3, for Scenario 1 and Scenario 2 (as described in Table 5-6). The details of the results for both scenarios can be found in Table C – 3, Appendix C.



Scenario 1 – Private parking building



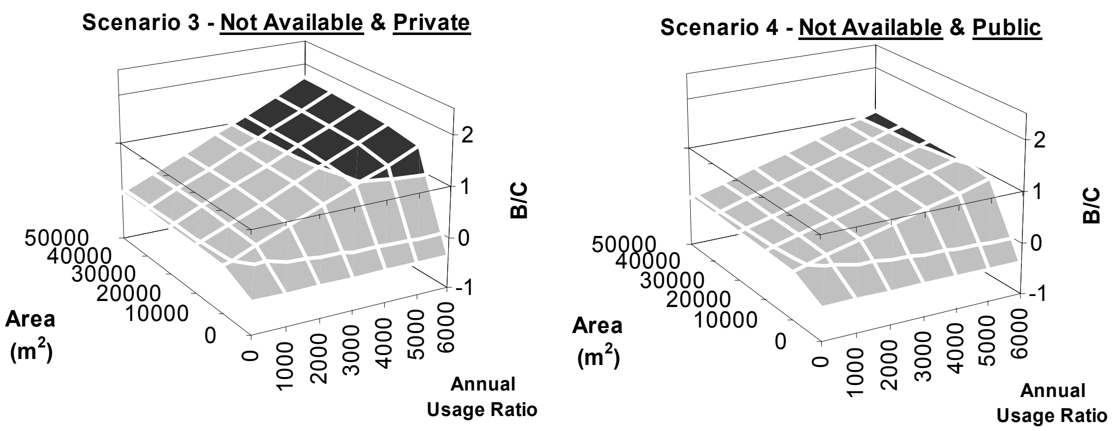
Scenario 2 – Public parking building

Figure 5-3: CBA results for sprinkler extension available: Scenario 1 (Private) and Scenario 2 (Public) – From Table C – 3, Appendix C

In Scenario 1, the cost-benefit ratio reaches 1 at the annual usage ratio of approximately 3,500. In Scenario 2, the cost-benefit ratio gets to 1 at the annual usage ratio of around 5,000. One would consider these annual usage ratios as significantly high, in comparison to a real annual usage ratio value of 350 found in section 4.3.1.3. The provision of sprinklers in the parking building would be considered economically unacceptable from the perspective of parking building owner.

5.7.2 Sprinkler Extension Not Available – Scenario 3 (Private) and Scenario 4 (Public)

The results from Equation 5-16 can be seen in Figure 5-4, for Scenario 3 and Scenario 4 (as described in Table 5-6). The details of the results for Scenario 3 and Scenario 4 are shown in Table C – 4 and Table C – 5 respectively, in Appendix C.



Scenario 3 – Private parking building Scenario 4 – Public parking building

Figure 5-4: CBA results for sprinkler extension not available: Scenario 3 (Private) and Scenario 4 (Public) – From Table C – 4 and Table C – 5, Appendix C

In Scenario 3, the cost-benefit ratio starts to reach 1 for the parking building with a total floor area of more than 3,000 m^2 and an annual usage ratio of around 6,000. When the total floor area of a parking building gets to 50,000 m^2, the cost-benefit ratio reaches 1 at the annual usage ratio of approximately 3,500.

In Scenario 4, the cost-benefit ratio starts to reach 1 for the parking building with a total floor area of more than 20,000 m^2 and an annual usage ratio of around 6,000.

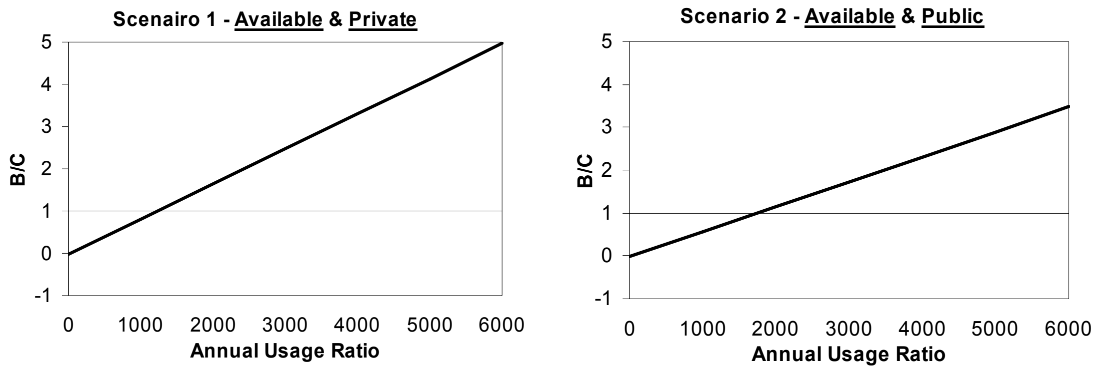
When the total floor area of a parking building gets to 50,000 m^2, the cost-benefit ratio reaches 1 at the annual usage ratio of approximately 5,500.

Similar to Scenario 1 and 2, the annual usage ratios at which cost-benefit ratios reach 1 in these two scenarios are considered quite high. The provision of sprinklers in the parking building would again be considered economically unacceptable from the perspective of parking building owner.

5.7.3 Closed Parking Building – Four Scenarios

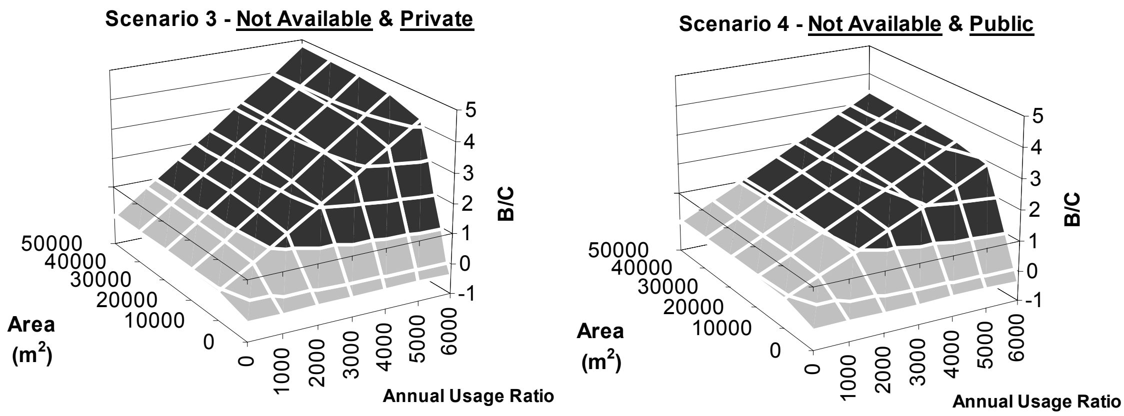
The results presented in the previous two sections were based on probabilities from FIRS data, which do not report the openness of the parking building. However the studies by Schleich et al. (1999) and Steinert (2000), as reviewed in section 2.1, indicate that without the intervention, the fire spread between parked vehicles tend to occur in a closed parking building. This was also suggested by the works of BHP (1987) and Kitano et al. (2000) which were also reviewed in section 2.2. The historical case studies about vehicle fire incidents in closed parking buildings, presented in section 1.3, further highlight the issue of fire spread within the closed parking building. It is therefore necessary to investigate the effect in the cost-benefit analysis by considering the likely fire spread in the situation of a closed parking building.

For closed parking buildings, the probabilities for the branch of Spread in the pathway of Fire Spread in the event for non-sprinklered parking building (Figure 4-2) were all changed to 100%. Based on the assumption that sprinklers can confine the fire within single vehicle, the event tree for a sprinklered parking building (Figure 4-3) can still be applied. Therefore $\sum (f \times n)$ in Table 5-7 was 2.75×10^{-7} for private buildings and 1.93×10^{-7} for public buildings respectively, while other parameters in this table stayed unchanged. The results from cost-benefit analysis, for all four scenarios in Table 5-6, are shown in Figure 5-5. Further details of the results can be found in Table C – 6 (Scenario 1 and 2), Table C – 7 (Scenario 3) and Table C – 8 (Scenario 4) in Appendix C.



Sprinkler extension available

Scenario 1 – Private parking building   Scenario 2 – Public parking building



Sprinkler extension not available

Scenario 3 – Private parking building   Scenario 4 – Public parking building

Figure 5-5: CBA results of closed parking building for all four scenarios (From Table C – 6, Table C – 7 and Table C – 8, Appendix C)

In Scenario 1 and 2, the cost-benefit ratio reaches 1 at the annual usage ratio (R) of approximately 1,500 and 2,000 respectively.

In Scenario 3 and 4, for the parking building with a total floor area of more than 1,000 m^2, the cost-benefit ratio starts to reach 1 at the annual usage ratio of 4,000 and 5,500 respectively. For Scenario 3, B/C also begins to reach 1 at the annual usage ratio of 1,500, when the total floor area of a parking building gets to 8,000 m^2. For Scenario 4, B/C begins to reach 1 at the annual usage ratio of 2,000, when the total floor area gets to 20,000 m^2.

These annual usage ratios are significantly lower than those values from the results based on FIRS data, presented in section 5.7.1 and 5.7.2. So the sprinkler system appears to start to justify itself in the closed parking building, where fire spread between vehicles is considered as an expected event. It should be noted that this analysis is not based on the statistical data from FIRS, and one needs to take caution when interpreting these results.

5.8 A Case Study Using @RISK

5.8.1 The Parking Building in Consideration

Based on the cost-benefit analysis model introduced earlier in the chapter, further analysis was performed for a public parking building with an overall floor area of 30,000 m^2 using Monte-Carlo simulation in @RISK software (Palisade, 2002b). A parking building of this size can provide over 1,000 parking spaces with an Efficiency of 29 m^2/space and is generally considered as a large size parking building in New Zealand. In terms of the extension from the existing sprinkler system, two scenarios were considered, which were Available and Not Available. These correspond to Scenario 2 and Scenario 4 as defined in Table 5-6. For Scenario 2 where the extension from an existing system is available, the total floor area (A) is irrelevant in the analysis as discussed in section 5.6.2.

5.8.2 Introduction to @RISK Programme

@RISK software is an “add-on” application in the EXCEL programme. In @RISK, each input variable is assigned a probability distribution, which effectively includes the uncertainty of every input in the analysis. The model is then run in the @RISK programme using the technique of Monte Carlo simulation and results with all possible outcomes are generated. The Monte Carlo simulation in @RISK can be visualised as running a large number of “what-if” analyses at the same time.

5.8.3 Inputs

For each input, Table 5-8 shows the probability distribution type with relevant statistical parameters such as minimum, mean (or expected value), maximum and standard deviation. These inputs are those appearing in Equation 5-15 (section 5.6.2), Equation 5-16 (section 5.6.3) and in Table 5-7 (section 5.6.4); the probability distribution was defined in @RISK programme for each input. Scenario 4 (sprinkler extension not available) has two more inputs than Scenario 2 (sprinkler extension available). These two inputs are annual fixed maintenance cost (M_F) and fixed initial cost (I_F) for sprinklers.

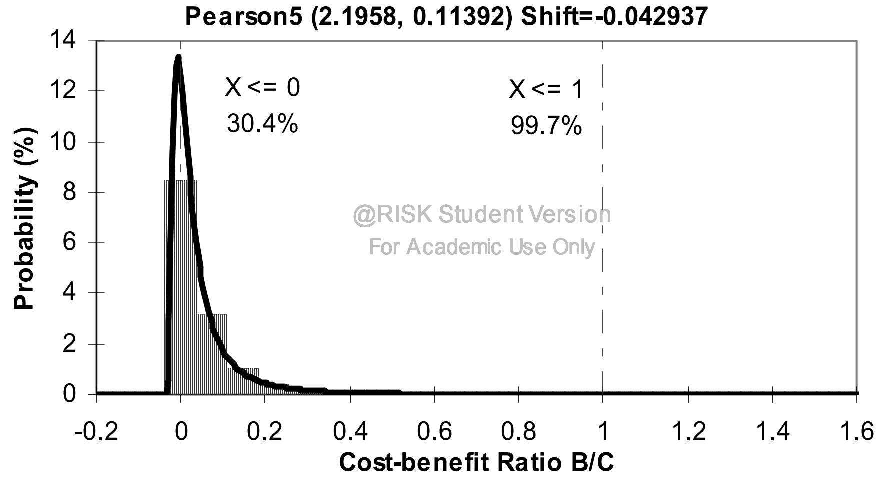
Table 5-8: Details of probability distribution for each input in @RISK

Input Description	Statistics				
	Distribution type	Minimum	Mean	Maximum	Standard Deviation
For Scenario 2 (sprinkler extension available) and Scenario 4 (sprinkler extension not available)					
Non-sprinklered – $\sum f \times n$	Normal	0	7.14×10^{-8}	+indefinite	7.14×10^{-9}
Sprinklered – f_s	Normal	0	7.14×10^{-8}	+indefinite	7.14×10^{-9}
Unit fire damage – D	Triangle	23	3870	11536	-
Reduction percentage – p	Normal	0.00	0.15	1.00	0.015
Annual marginal maint. – M_m	Triangle	0.020	0.025	0.030	-
Marginal initial – I_m	Triangle	10	12	14	-
Discount rate – i	Triangle	0.05	0.10	0.15	-
Annual usage ratio – R	Lognormal	0	350	+indefinite	350
For Scenario 4 (sprinkler extension not available) only					
Annual fixed maint. – M_F	Triangle	500	750	1000	-
Fixed initial – I_F	Triangle	15000	20000	25000	-

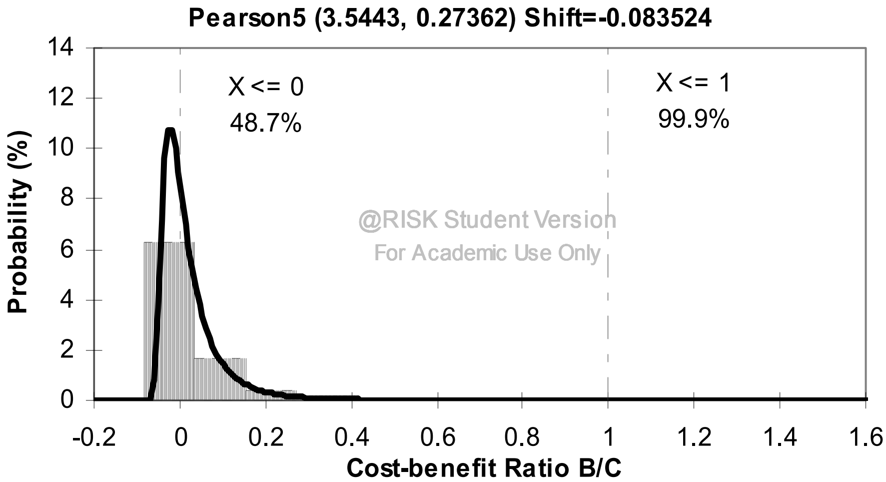
The type of probability distribution for each input is based on engineering judgements, except for unit fire damage (D). The mean of each distribution is taken as the corresponding value in Table 5-7 for each input. The minimum and maximum for each distribution are also assumed values, except for unit fire damage (D). For normal distribution type, the standard deviation is taken as 10% of the mean value. Unit fire damage (D) is represented by the triangle distribution, which is also used to fit the historical fire damage in Figure 5-1. The mean value is taken as the unit fire damage value derived in section 5.2.4.2. The values of minimum and maximum are obtained from the 1972 US data in Table 5-2 using the same method for deriving unit fire damage value as shown in section 5.2.4.2. The distribution graph from @RISK programme for each input can also be found in Table C – 9, Appendix C.

5.8.4 Output Results

The cost-benefit ratios (B/C) in Equation 5-15 and Equation 5-16 were identified as the outputs in @RISK programme, for both scenarios which are extension from existing sprinklers Available (Scenario 2) and Not Available (Scenario 4).



Sprinkler Extension Available



Sprinkler Extension Not Available

Figure 5-6: The distribution of cost-benefit ratio from @RISK for a public parking building (30,000m^2) for both scenarios (From Table C – 10 and Table C – 11, Appendix C)

The distributions of output results from @RISK, as shown in Figure 5-6, are similar for both scenarios. The distribution type of Pearson5 fits both results according to goodness-of-fit tests in @RISK. This seems to relate to the probability distribution of annual usage ratio (R), which is a Lognormal type. The mean of cost-benefit ratio is 0.049 for the scenario of sprinkler extension available and 0.026 for the scenario of sprinkler extension not available.

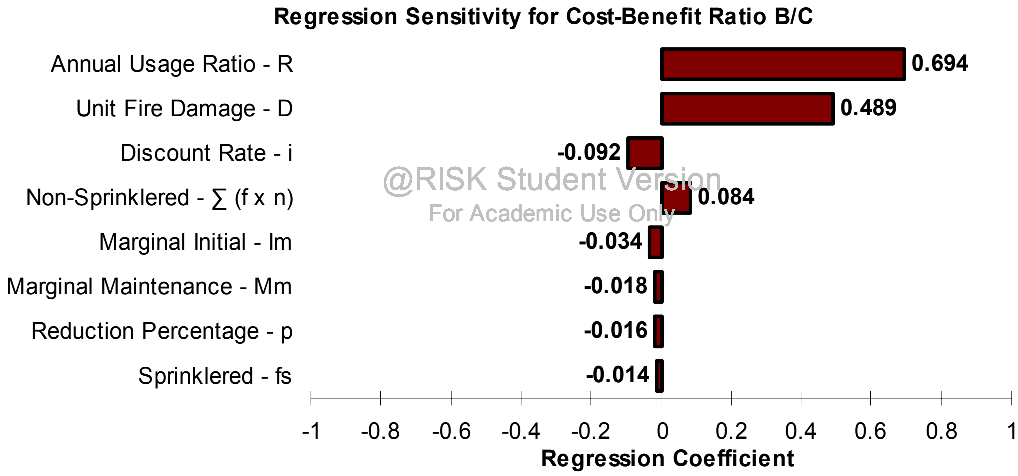
Figure 5-6 also indicates that for sprinkler extension available (Scenario 2), the cumulative probability is 99.7% when cost-benefit ratio is less than 1. For sprinkler extension not available (Scenario 4), the cumulative probability is 99.9%, for cost-benefit ratio being less than 1. Hence, the probability of cost-benefit ratio exceeding the value of 1 is 0.3% for Scenario 2 and 0.1% for Scenario 4 situation. For both scenarios, the provision of sprinklers would be considered economically unacceptable for this public parking building with a total floor area of 30,000 m^2.

The statistical details of output result for both scenarios can be found in Table C – 10 for Scenario 2 and Table C – 11 for Scenario 4 in Appendix C.

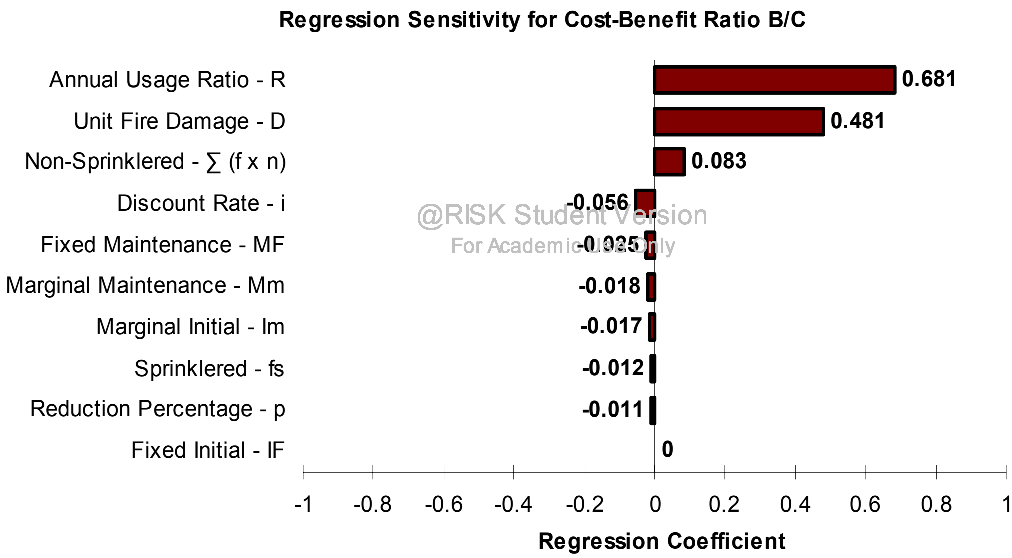
5.8.5 Sensitivity Analysis of Inputs

The regression tornado graphs in Figure 5-7 show the regression sensitivity of each input for both scenarios. Each input is ranked according to how sensitive the cost-benefit ratio is to the input distribution.

The coefficients shown in the regression tornado graphs are normalized regression coefficients associated with each input. A regression value of 0 indicates that there is no significant relationship between the input and the cost-benefit ratio. A regression value of 1 or -1 shows that there is a standard deviation change of 1 or -1 in the cost-benefit ratio, for a standard deviation change of 1 in the input. The regression sensitivity results from @RISK show that annual usage ratio (R) has the most influence on the output of cost-benefit ratio, for both scenarios. For Scenario 2, the next three critical inputs by ranking are unit fire damage (D), discount rate (i), and non-sprinklered $\sum (f \times n)$. For Scenario 4, the next three critical inputs by ranking are unit fire damage (D), non-sprinklered $\sum (f \times n)$, and discount rate (i).



Sprinkler Extension Available (Scenario 2)



Sprinkler Extension Not Available (Scenario 4)

Figure 5-7: Ranking of inputs by regression sensitivity for both scenarios (From Table C – 12 and Table C – 13, Appendix C)

In regression tornado graphs for both scenarios, there are three inputs having a positive impact on the output of cost-benefit ratio. Those inputs are annual usage ratio (R), unit fire damage (D), and $\sum f \times n$ for non-sprinklered.

Chapter 6 Conclusions

6.1 Statistics from FIRS Data

During the eight-year period from 1995 to 2003, there were a total of 96 fire incidents in New Zealand parking buildings involving vehicles or on average 12 vehicle fire incidents each year in New Zealand parking buildings. There were a total of eight vehicles involved in three multiple vehicle fire incidents, which equate to approximately 3% of total vehicle fire incidents in New Zealand parking buildings.

The four leading causes of vehicle fires in parking buildings were found to be deliberately lit, electrical faults, mechanical failure or malfunction, and carelessness.

The average age of vehicles involved in New Zealand parking building fires was 14.3 years old. It was also found that the probability of a vehicle being involved in a parking building fire rises with the increase of the vehicle age.

6.2 Risk Assessment of Vehicle Fires in Parking Buildings

Event tree analysis was carried out for vehicle fire risks in New Zealand parking buildings. The frequency of vehicle fires in New Zealand parking buildings was estimated to be 1.71×10^{-7} per each visit. Annual vehicle fire frequencies in New Zealand parking buildings are lower than those in the buildings of other occupancies when annual usage ratio for the parking building is relatively low, and increases with the annual usage ratio.

The cost-benefit analysis for the provision of sprinklers in the parking building was performed based on the FIRS statistics and event tree analysis of vehicle fires in New Zealand parking buildings. The analysis indicated that the automatic sprinkler system generally does not justify itself, from the building owner's point of view for both private and public type buildings. This appears to agree with the requirement placed by *Acceptable Solution (C/AS1)* in New Zealand Building Code, where the provision of sprinklers is non-mandatory. The sensitivity analysis of cost-benefit analysis, for a public parking building with a total floor area of 30,000 m^2 in the case study, shows that the annual usage ratio is the most critical factor in the cost-benefit analysis.

Chapter 7 Discussions and Recommendations

7.1 General

As discussed in section 1.1, this report attempts to answer those questions about vehicle fires in parking buildings, which were raised from the internet news groups' discussion within international fire safety engineering community, in a New Zealand context. The statistics of vehicle fires in parking buildings in Chapter 3 provides the answers to likelihood of vehicle fires/fire spreads, causes of vehicle fires, and materials involved in fire. The literature review in Chapter 2 covers the severity of the vehicle fires in a parking building situation. The cost-benefit analysis in Chapter 5 investigates the appropriateness of sprinkler provision in the parking building from the perspective of property protection and building owner's point of view.

7.2 Life Safety vs. Property Protection

In this research, the result from the cost-benefit analysis agrees with the requirement placed by *Acceptable Solution (C/AS1)* in New Zealand Building Code; however it should be noted that the building code is primarily concerned with the provision of the life safety. Therefore it is also necessary to evaluate the effect of vehicle fire on life safety in the parking building, although the statistics in both New Zealand and the US do not indicate any fatality in such circumstance. All the experimental work reviewed in section 2.2 was concerned with the property protection in the event of a vehicle fire. In this research, literature about the effect of vehicle fire on life safety in the parking building was not found. Future research is hence recommended to investigate the life safety issue in the event of a parking building vehicle fire. For example, the effect of sprinkler activation on smoke production can be one of the subjects as the experiments reviewed in section 2.2 show the contradictory results.

7.3 Method of Entering Data of Vehicle Fire Incidents into FIRS

A vehicle fire inside a parking building, where the equipment being involved is recorded as a motor vehicle, should be classified as a structure fire rather than being classified as a mobile property fire. Structure fires should have a higher priority than mobile property fires because of the potential property loss. This will also provide the useful information such as the impact of vehicle fires on the building and the performance of fire protection measures etc. for later study of these fire incidents.

7.4 Vehicle Design Fire

When a design fire is represented by the t-squared fire, the expected growth rate is to be a value between slow and medium growth rate based on the literature reviews carried out in this research. The peak HRR can vary from approximately 4 MW to 9 MW, depending on the amount of energy to be released from the vehicle in consideration. If the ventilation condition is close to that in a closed car park, the fire spread between vehicles is to be considered.

The design fire indicates the potential severity to be reached in a vehicle fire and highlights the necessity of assessing the life safety in the situation of a vehicle fire in the parking building.

7.5 Event Tree Model

The prerequisite of the fire spread between vehicles is that vehicles in consideration are parked next to each other. When a vehicle catches fire and there are no neighbouring vehicles, the fire spread to other vehicles is not likely to happen. Therefore the density of vehicle parking in a non-sprinklered parking building would affect the probabilities of fire spread between vehicles. To simplify the event tree model, it is assumed that there are always vehicles adjacent to the one first ignited. As a result, certain probabilities were assigned to the pathway of Fire Spread in the event tree for a non-sprinklered parking building (Figure 4-2). Since current model assumes a maximum potential for car-to-car fire spread due to neighbouring vehicles, it is likely that the model gives a higher benefit to sprinklers than where the probability of car-to-car fire spread is a function of parking density. It is hence recommended to incorporate the variation of the parking density into the event tree model in the future research.

7.6 Consideration of the Loss of Business

The cost-benefit analysis in this research does not consider the loss of business caused by a vehicle fire in the parking building, as discussed in section 5.1. Nevertheless, for a parking building with relative large capacity (total floor area) and high occupancy (annual usage ratio), the provision of sprinklers already becomes economically justified without considering the loss of business, as shown by analysis results in section 5.7. On the other hand, the loss of business probably does not have a significant impact on the analysis results for a parking building with large capacity and low usage, where the parking spaces not affected by the fire damage can always be utilised.

The inclusion of the loss of business may affect the analysis results for a parking building of small capacity. Nevertheless, such parking buildings tend to be private type parking buildings and the loss of business may not be a concern as it would have been for those parking buildings owned by the parking operators etc.

7.7 Provision of Smoke Control System

Various case studies and experiments have highlighted the potential hazard to human life safety posed by the extensive smoke production in a vehicle fire, particularly in the situation of a closed parking building. It is therefore necessary to install the appropriate smoke control system in the enclosed parking building especially when the sprinkler system is not provided, so that tenable conditions can be provided for both occupants and fire-fighters. This is also required by the *Acceptable Solution (C/AS1)* in New Zealand Building Code for this particular situation.

When applying the cost-benefit analysis methodologies presented in this report for a particular parking building, one needs to obtain appropriate annual usage ratio (R), discount rate (i), non-sprinklered $\sum (f \times n)$, and unit fire damage (D) for the building under consideration, such that a more accurate result of cost-benefit ratio can be found.

7.8 Areas for Future Research

Future research is recommended in the following areas:

- Statistical analysis of general vehicle fire incidents. There were 26,969 of such fires in New Zealand from 1995 to 2003 according to FIRS database

- Carry out experiments on newer cars to investigate:

    - Severity of car fires
    - Potential of car-to-car fire spread
    - Effectiveness of sprinklers on car fires
    - Impact of car firs on property protection and life safety

- Incorporate the variation of the parking density into the event tree model

- Improve the cost-benefit model by:

    - Incorporating the financial data for interruption or loss of the business caused by vehicle fires in parking buildings
    - Incorporating insurance premium reduction by the provision of sprinklers to a parking building
    - Obtaining more data for the cost of fire damage to the parking building

    - Assigning distribution to key parameters based on relevant data instead of engineering assumption when performing case study

- Obtain the statistical data of annual usage ratio, which is the most critical input for the cost-benefit analysis according to the results of regression sensitivity from the case study in section 5.8.5

- Evaluate the impact on life safety by a vehicle fire in the parking building. A series of fire scenarios can be devised to incorporate the design fire, openness of the structure, building geometry, provision of fire safety system, and escape route etc. These scenarios can be run in certain zone/field computer models and calculations of RSET (required safe escape time) and ASET (available safe escape time) can be made accordingly.

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Appendix A Statistical Details of Vehicle Fires in New Zealand Parking Buildings, 1995 - 2003

The terminologies used in the breakdown of statistical details are from the descriptions in *New Zealand Fire Service Fire Incident Reporting System Instruction & Coding Manual* (New Zealand Fire Service, 1995).

Table A – 1: Specific type of parking buildings where vehicles were involved in fires, 1995 – 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Private fleet carpark: Car, Bus, Truck (Single level - covered)	9	11	11	11	9	3	1	6	61
Public carpark: Multi-storied above ground	5	1	1	1	0	0	3	3	14
Public carpark: Single level - covered	0	2	2	4	2	1	0	1	12
Public carpark: Multi-storied below ground	1	0	3	0	1	1	1	0	7
Public carpark: Multi-storied above and below ground	1	4	1	0	1	0	0	0	7
TOTAL	16	18	18	16	13	5	5	10	101

Table A – 2: Supposed causes of vehicles fires in parking buildings, 1995 – 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Deliberately lit	2	6	1	5	6	1	1	5	27
Electrical faults	6	3	8	3	1	2	0	2	25
Mechanical failure or malfunction	4	3	3	1	1	1	3	1	17
Carelessness	1	4	2	2	1	1	1	1	13
Unknown	3	1	2	5	1	0	0	0	12
Others	0	1	2	0	3	0	0	1	7
TOTAL	16	18	18	16	13	5	5	10	101
Deliberately lit									
Unlawful	2	4	0	3	2	0	1	4	16
Suspicious	0	2	1	2	4	1	0	1	11
Electrical faults									
Short circuit, earth fault	6	2	7	3	1	1	0	0	20
Other electrical failure	0	1	1	0	0	1	0	2	5
Mechanical failure or malfunction									
Part failure, leak or break	4	3	0	1	1	0	1	1	11
Equipment not being operated properly	0	0	1	0	0	0	1	0	2
Installed too close to combustibles	0	0	0	0	0	1	0	0	1
Other installation deficiency	0	0	1	0	0	0	0	0	1
Equipment overloaded	0	0	0	0	0	0	1	0	1
Lack of maintenance	0	0	1	0	0	0	0	0	1
Carelessness									
Careless disposal: cigarettes, cigars, ashes, embers	0	1	0	0	0	1	0	1	3
Heat source too close to combustibles: fires under trees, welding/cutting operations, debris	0	0	0	2	0	0	1	0	3

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Combustible placed too close to heat source	0	1	1	0	0	0	0	0	2
Failure to use ordinary care	0	1	0	0	1	0	0	0	2
Reckless act	0	0	1	0	0	0	0	0	1
People playing with heat sources	1	0	0	0	0	0	0	0	1
Flammable liquid/gas spilled or accidentally released	0	1	0	0	0	0	0	0	1
Unknown									
Unknown	2	1	2	4	1	0	0	0	10
Unable to classify	0	0	0	1	0	0	0	0	1
Not Recorded	1	0	0	0	0	0	0	0	1
Others									
Exposure fire	0	0	0	0	3	0	0	0	3
Backfire	0	1	0	0	0	0	0	1	2
Friction	2		0	0	2	0	0	0	0

Table A – 3: Vehicles fires in parking buildings by number of vehicles involved, 1995 – 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Single	14	18	18	16	9	5	5	8	93
Multiple	2	0	0	0	4	0	0	2	8
All	16	18	18	16	13	5	5	10	101

Table A – 4: Type of vehicles involved in fires in parking buildings, 1995 – 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Car, Taxi, Ambulance	0	12	15	10	4	3	5	8	57
Unknown	16	1	0	2	3	0	0	1	23
Other Vehicles	0	4	2	4	3	2	0	0	15
Bus	0	1	1	0	3	0	0	1	6
TOTAL	16	18	18	16	13	5	5	10	101
Unknown									
Not Recorded	16	1	0	2	3	0	0	0	22
Unable to Classify	0	0	0	0	0	0	0	1	1
Other Vehicles									
Truck: One tonne and over, Fire appliance	0	2	2	3	2	1	0	0	10
Light truck: Under one tonne, Ute, Van, Wagon	0	2	0	1	1	0	0	0	4
Waste container, Bin, Compacter, Dumper	0	0	0	0	0	1	0	0	1

Table A – 5: Distribution comparison between age of vehicles involved in parking building fires from 1998 to 2003 and age of all registered vehicles in 1998

Age of vehicle	Percentage of vehicles involved in fires in parking building, 1995-2003	Percentage of vehicles registered in NZ as at 1st January 1998
0 to 2	4%	7%
3 to 5	8%	11%
6 to 10	19%	33%
11 to 15	37%	29%
16 to 20	17%	12%
21 to 25	4%	4%
26 to 30	6%	2%
over 30	6%	2%

Table A – 6: Mean age for major vehicles in New Zealand from 1998 to 2002 (New Zealand Registrar of Motor Vehicles, 2003)

Year	Mean age of major vehicle types in New Zealand (years)							Average of all types (years)
	Cars	Trucks	Buses	Motor Caravans	Motorcycles	Mopeds	Trailers	
1998	11.2	11.7	12.9	18.2	13.9	13.5	15.9	13.9
1999	11.28	12.01	12.87	18.08	14.37	13.74	16.04	14.1
2000	11.42	12.25	13.03	18.44	14.83	13.94	16.28	14.3
2001	11.55	12.47	13.18	18.21	15.25	13.98	16.51	14.5
2002	11.63	12.57	13.19	18.26	15.54	13.79	16.72	14.5

Table A – 7: Vehicle fires in parking buildings by day of week, 1995 – 2003

All									
	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Monday	0	2	0	2	0	1	1	1	7
Tuesday	0	3	3	6	5	0	0	1	18
Wednesday	1	2	3	1	1	1	0	0	9
Thursday	2	4	3	2	0	1	0	2	14
Friday	5	3	4	2	5	1	2	2	24
Saturday	6	2	2	2	0	1	0	1	14
Sunday	2	2	3	1	2	0	2	3	15
TOTAL	16	18	18	16	13	5	5	10	101
Private Parking									
	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Monday	0	2	0	2	0	0	0	0	4
Tuesday	0	3	2	2	4	0	0	0	11
Wednesday	1	1	1	1	1	1	0	0	6
Thursday	1	3	2	1	0	1	0	2	10
Friday	3	0	4	2	3	1	1	2	16
Saturday	3	1	1	2	0	0	0	0	7
Sunday	1	1	1	1	1	0	0	2	7
TOTAL	9	11	11	11	9	3	1	6	61
Public Parking									
	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Monday	0	0	0	0	0	1	1	1	3
Tuesday	0	0	1	4	1	0	0	1	7

Wednesday	0	1	2	0	0	0	0	0	3
Thursday	1	1	1	1	0	0	0	0	4
Friday	2	3	0	0	2	0	1	0	8
Saturday	3	1	1	0	0	1	0	1	7
Sunday	1	1	2	0	1	0	2	1	8
TOTAL	7	7	7	5	4	2	4	4	40

Table A – 8: Vehicle fires in parking buildings by time of day, 1995 – 2003

Time	00:00 to 01:00	01:00 to 02:00	02:00 to 03:00	03:00 to 04:00	04:00 to 05:00	05:00 to 06:00	06:00 to 07:00	07:00 to 08:00	08:00 to 09:00	09:00 to 10:00	10:00 to 11:00	11:00 to 12:00	12:00 to 13:00	13:00 to 14:00	14:00 to 15:00	15:00 to 16:00	16:00 to 17:00	17:00 to 18:00	18:00 to 19:00	19:00 to 20:00	20:00 to 21:00	21:00 to 22:00	22:00 to 23:00	23:00 to 00:00	TOTAL
Private	2	2	0	2	2	2	2	3	2	3	1	2	1	6	4	4	4	0	1	5	4	3	4	2	61
Public	1	0	0	1	0	1	1	1	1	1	1	1	5	3	3	3	2	4	1	3	3	2	1	1	40
All	3	2	0	3	2	3	3	4	3	4	2	3	6	9	7	7	6	4	2	8	7	5	5	3	101

Table A – 9: Heat sources involved in vehicles fires in parking buildings, 1995 – 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Short circuit arc	7	4	11	3	1	2	3	2	33
Match, lighter & cigarettes	3	2	2	4	4	1	0	5	21
Exposure fire	2	3	2	3	7	1	0	0	18
Hot object	2	6	3	4	0	0	1	1	17
Flame	0	3	0	1	1	1	0	1	7
Not Recorded	2	0	0	1	0	0	1	1	5
TOTAL	16	18	18	16	13	5	5	10	101
Short circuit arc									
Short circuit arc: Unspecified	4	1	6	2	1	1	2	2	19
Short circuit arc: Mechanical damage	3	2	3	1	0	1	1	0	11
Short circuit arc: Defective or worn installation	0	0	2	0	0	0	0	0	2
Short circuit arc: Water cause	0	1	0	0	0	0	0	0	1
Match, lighter & cigarettes									
Match	3	2	2	3	3	0	0	1	14
Lighter: Flame type	0	0	0	1	1	0	0	1	3
Lighter, match, candle - Possible combination of	0	0	0	0	0	0	0	2	2
Cigarette	0	0	0	0	0	1	0	1	2
Exposure fire									
Exposure Fire - unable to classify	1	3	2	3	3	1	0	0	13
Exposure fire: Radiated heat	1	0	0	0	3	0	0	0	4
Exposure fire: Conducted heat	0	0	0	0	1	0	0	0	1
Hot object									
Heat from liquid fuelled equipment	1	3	1	1	0	0	0	0	6
Heat from electrical equipment: Improperly operating	0	1	1	1	0	0	0	0	3

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Heat from smoking material	0	1	0	2	0	0	0	0	3
Friction heat, Overheated tyres	0	1	1	0	0	0	0	0	2
Hot object - not classified above	0	0	0	0	0	0	1	1	2
Heat from electrical equipment: Properly operating	1	0	0	0	0	0	0	0	1
Flame									
Flame escaping from liquid fuelled equipment, Backfire	0	1	0	0	1	0	0	1	3
Coal or coke fuelled equipment: Spark, Ember, Flame, Chimney spark	0	1	0	0	0	0	0	0	1
Gas or liquid powered cutting torch: Spark, Ember, Flame	0	0	0	1	0	0	0	0	1
Flame from gas equipment other than a torch	0	0	0	0	0	1	0	0	1
Outside fire - unable to classify	0	1	0	0	0	0	0	0	1

Table A – 10: Object first ignited in vehicles fires in parking buildings, 1995 – 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Unknown	3	6	4	5	7	1	1	0	27
Electrical components	5	1	10	3	1	2	2	2	26
Flammable liquid and gases (not aerosols or propellants)	3	4	1	1	2	0	1	3	15
Others	2	3	2	4	1	0	0	2	14
Upholstery and soft goods	1	2	0	1	2	1	1	3	11
Structure components	2	2	1	2	0	1	0	0	8
TOTAL	16	18	18	16	13	5	5	10	101
Unknown									
Unknown	2	6	4	5	7	1	0	0	25
Not Recorded	1	0	0	0	0	0	1	0	2
Electrical components									
Electrical wire, Wiring insulation	5	1	10	3	1	2	0	1	23
Power transfer and electrical equipment - not classified above	0	0	0	0	0	0	1	1	2
Electronic componentry	0	0	0	0	0	0	1	0	1
Others									
Multiple items	0	2	0	2	0	0	0	1	5
Rubbish, Garbage, Waste	0	1	0	1	0	0	0	0	2
Luggage: Suitcase, Travel bag, Backpack	1	0	0	0	0	0	0	0	1
Newspaper, Magazine, Files	0	0	1	0	0	0	0	0	1
Paper, excluding newspaper or rolled paper	0	0	0	0	0	0	0	1	1
Tarpaulin, Tent, Marquee	1	0	0	0	0	0	0	0	1
Pyrotechnics, Explosives, Fireworks	0	0	0	0	1	0	0	0	1
Propellant, Aerosol, Hairspray	0	0	0	1	0	0	0	0	1
Tyre	0	0	1	0	0	0	0	0	1
Upholstery and soft goods									
Upholstered: Chairs, Sofas, Beds, Vehicle seats	0	1	0	1	0	1	0	2	5

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Clothing (Not being worn)	1	0	0	0	1	0	0	0	2
Non made up goods including fabrics and yarn	0	1	0	0	1	0	0	0	2
Un-upholstered: Chairs, Sofas, Beds, Vehicle seats	0	0	0	0	0	0	0	1	1
Bedding: Blankets, Sheets, Duvet	0	0	0	0	0	0	1	0	1
Structure components									
Thermal Insulation: Batts, Loose fill (within walls or ceiling)	2	1	0	1	0	0	0	0	4
Floor coverings: Carpets, Mats, Rugs	0	1	0	0	0	0	0	0	1
Framing, Structural member, Interior walls and doors	0	0	0	0	0	1	0	0	1
Lagging: Conduit covering, Other insulating material	0	0	1	0	0	0	0	0	1
Awning, Canopy	0	0	0	1	0	0	0	0	1

Table A – 11: Material first ignited in vehicles fires in parking buildings from 1995 to 2003

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Unknown	3	6	4	6	6	1	2	0	28
PVC: Floor tiles, Guttering, Pipes, Plastic bags, Electrical insulation	8	2	9	3	1	2	1	1	27
Upholstery and soft goods	2	3	1	2	2	1	1	4	16
Flammable liquid	2	4	1	2	2	0	1	3	15
Others	1	3	3	3	2	1	0	2	15
TOTAL	16	18	18	16	13	5	5	10	101
Unknown									
Unknown	2	6	4	6	6	1	0	0	25
Not Recorded	1	0	0	0	0	0	2	0	3
Upholstery and soft goods									
Vinyl: Plastic coated fabrics, Upholstery fabrics (not floor covering)	0	0	1	2	0	0	0	1	4
Fabric, Fibre (finished)	0	1	0	0	2	1	0	0	4
Polyurethane: Furnishings, Upholstery, Mattresses	0	0	0	0	0	0	0	3	3
Cotton, Canvas, Rayon (not oiled canvas)	1	1	0	0	0	0	1	0	3
Wool, Wool mixtures (finished goods)	1	1	0	0	0	0	0	0	2
Flammable liquid									
Petrol	1	3	1	2	2	0	1	2	12
Flammable liquid: Kerosene, Methylated spirit, Ethanol, Turpentine	0	1	0	0	0	0	0	1	2
Combustible liquid: Linseed, Lubricant, Cooking oil	1	0	0	0	0	0	0	0	1
Others									
Multiple materials first ignited	0	2	0	2	1	0	0	0	5
Rubbish (material having no value in the same container or pile)	0	1	0	0	0	0	0	2	3
Rubber	0	0	2	0	0	0	0	0	2

	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	TOTAL
Wood: sawn, finished timber	0	0	0	0	0	1	0	0	1
Plywood	1	0	0	0	0	0	0	0	1
Treated paper: building paper, wax or tar paper, wall paper	0	0	1	0	0	0	0	0	1
Waterproof canvas	0	0	0	0	1	0	0	0	1
Oily rags	0	0	0	1	0	0	0	0	1

Appendix B Data for Event Tree Analysis

Table B – 1: Number of vehicles registered in New Zealand from 1996 to 2002 (New Zealand Registrar of Motor Vehicles, 2003)

Calendar Year	Number of Vehicles
1996	2419807
1997	2441956
1998	2547795
1999	2702678
2000	2735981
2001	2766534
2002	2841301
2003	-

Table B – 2: Survey results – Number of parking buildings in New Zealand

Area	District Council	Private Parking Operator
	Public	Public
Auckland	5	37
Christchurch	7	2
Dunedin	-	2
Hamilton	-	1
Queenstown	-	1
Rotorua	1	0
Tauranga	-	2
Timaru	1	1
Waitaki	0	0
Wellington	1	21

Appendix C Data and Results for Cost-Benefit Analysis (CBA)

Table C – 1: The trend of American Producer Price Index for industrial commodity from 1972 to 2003, reproduced from U.S. Department of Labor (2004)

Year	Annual PPI	Year	Annual PPI	Year	Annual PPI	Year	Annual PPI
1972	37.8	1980	88	1988	106.3	1996	127.3
1973	40.3	1981	97.4	1989	111.6	1997	127.7
1974	49.2	1982	100	1990	115.8	1998	124.8
1975	54.9	1983	101.1	1991	116.5	1999	126.5
1976	58.4	1984	103.3	1992	117.4	2000	134.8
1977	62.5	1985	103.7	1993	119	2001	135.7
1978	67	1986	100	1994	120.7	2002	132.4
1979	75.7	1987	102.6	1995	125.5	2003	139.1(P)

(P) – Preliminary

Table C – 2: Two fit results of vehicle fire damages in parking building fires from the 1972 US study

Triangle distribution fit

	Fit	Input
Function	=RiskTriang(100.00, 100.00, 50137)	N/A
min	100	N/A
m. likely	100	N/A
max	50136.7145290589	N/A
Minimum	100.00	100.00
Maximum	50137	50000
Mean	16779	496.71
Mode	100.00	100.00 [est]
Median	14755	100.00
Std. Deviation	11794	3389.4
Variance	139092933	11458635
Skewness	0.5657	12.3647
Kurtosis	2.4000	164.8347

Normal distribution fit

	Fit	Input
Function	=RiskNormal(496.71, 3389.4)	N/A
μ	496.708860759494	N/A
σ	3389.35356186207	N/A
Minimum	-Infinity	100.00
Maximum	+Infinity	50000
Mean	496.71	496.71
Mode	496.71	100.00 [est]
Median	496.71	100.00
Std. Deviation	3389.4	3389.4
Variance	11487717.6	11458635
Skewness	0.0000	12.3647
Kurtosis	3.0000	164.8347

Table C – 3: CBA results for sprinkler extension available: Scenario 1 (Private) and Scenario 2 (Public)

Annual Usage Ratio (R)	**Scenario 1**	**Scenario 2**
0	0.0	0.0
500	0.1	0.1
1000	0.3	0.2
1500	0.4	0.3
2000	0.6	0.4
2500	0.7	0.5
3000	0.9	0.6
3500	1.0	0.7
4000	1.2	0.8
4500	1.3	0.9
5000	1.5	1.0
5500	1.6	1.0
6000	1.8	1.1

Table C – 4: CBA results for sprinkler extension not available & private – Scenario 3

Annual Usage Ratio (R)	Total floor area of parking building (A, m²)									
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000
0	-0.4	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
500	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
1000	-0.4	-0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2
1500	-0.4	-0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3
2000	-0.4	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.4
2500	-0.4	0.0	0.2	0.3	0.4	0.5	0.5	0.5	0.5	0.6
3000	-0.4	0.1	0.3	0.4	0.5	0.6	0.6	0.6	0.7	0.7
3500	-0.4	0.2	0.4	0.5	0.6	0.7	0.7	0.8	0.8	0.8
4000	-0.4	0.2	0.5	0.6	0.7	0.8	0.8	0.9	0.9	0.9
4500	-0.4	0.3	0.6	0.7	0.8	0.9	1.0	1.0	1.0	1.1
5000	-0.4	0.3	0.6	0.8	0.9	1.0	1.1	1.1	1.2	1.2
5500	-0.4	0.4	0.7	0.9	1.0	1.1	1.2	1.2	1.3	1.3
6000	-0.4	0.4	0.8	1.0	1.1	1.2	1.3	1.4	1.4	1.4
Annual Usage Ratio (R)	Total floor area of parking building (A, m²)									
	10000	20000	30000	40000	50000					
0	-0.1	0.0	0.0	0.0	0.0					
500	0.1	0.1	0.1	0.1	0.1					
1000	0.2	0.2	0.2	0.3	0.3					
1500	0.3	0.4	0.4	0.4	0.4					
2000	0.4	0.5	0.5	0.5	0.5					
2500	0.6	0.6	0.7	0.7	0.7					
3000	0.7	0.8	0.8	0.8	0.8					
3500	0.8	0.9	1.0	1.0	1.0					
4000	1.0	1.1	1.1	1.1	1.1					
4500	1.1	1.2	1.2	1.3	1.3					
5000	1.2	1.3	1.4	1.4	1.4					
5500	1.3	1.5	1.5	1.6	1.6					
6000	1.5	1.6	1.7	1.7	1.7					

Table C – 5: CBA results for sprinkler extension not available & public – Scenario 4

Annual Usage Ratio (R)	Total floor area of parking building (A, m^2)									
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000
0	-0.4	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
500	-0.4	-0.2	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0
1000	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1
1500	-0.4	-0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
2000	-0.4	-0.1	0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.3
2500	-0.4	-0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.3
3000	-0.4	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.4
3500	-0.4	0.0	0.2	0.3	0.4	0.4	0.4	0.5	0.5	0.5
4000	-0.4	0.1	0.2	0.4	0.4	0.5	0.5	0.5	0.6	0.6
4500	-0.4	0.1	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7
5000	-0.4	0.1	0.3	0.5	0.6	0.6	0.7	0.7	0.7	0.7
5500	-0.4	0.2	0.4	0.5	0.6	0.7	0.7	0.8	0.8	0.8
6000	-0.4	0.2	0.5	0.6	0.7	0.8	0.8	0.9	0.9	0.9

Annual Usage Ratio (R)	Total floor area of parking building (A, m^2)									
	10000	20000	30000	40000	50000					
0	-0.1	0.0	0.0	0.0	0.0					
500	0.0	0.0	0.1	0.1	0.1					
1000	0.1	0.1	0.1	0.2	0.2					
1500	0.2	0.2	0.2	0.2	0.2					
2000	0.3	0.3	0.3	0.3	0.3					
2500	0.3	0.4	0.4	0.4	0.4					
3000	0.4	0.5	0.5	0.5	0.5					
3500	0.5	0.6	0.6	0.6	0.6					
4000	0.6	0.7	0.7	0.7	0.7					
4500	0.7	0.8	0.8	0.8	0.8					
5000	0.8	0.8	0.9	0.9	0.9					
5500	0.8	0.9	1.0	1.0	1.0					
6000	0.9	1.0	1.1	1.1	1.1					

Table C – 6: CBA results for closed parking buildings: Sprinkler extension available – Scenario 1 (Private) and Scenario 2 (Public)

Annual Usage Ratio (R)	Scenario 1	Scenario 2
0	0.0	0.0
500	0.4	0.3
1000	0.8	0.6
1500	1.2	0.9
2000	1.6	1.1
2500	2.1	1.4
3000	2.5	1.7
3500	2.9	2.0
4000	3.3	2.3
4500	3.7	2.6
5000	4.1	2.9
5500	4.6	3.2
6000	5.0	3.5

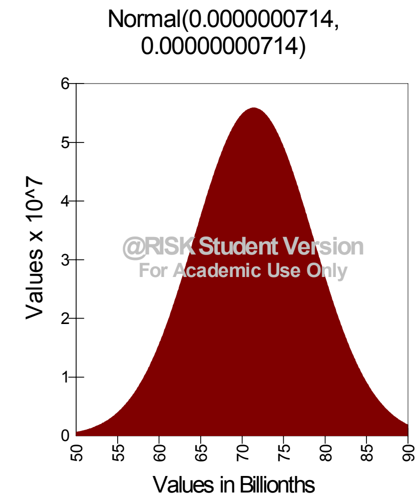
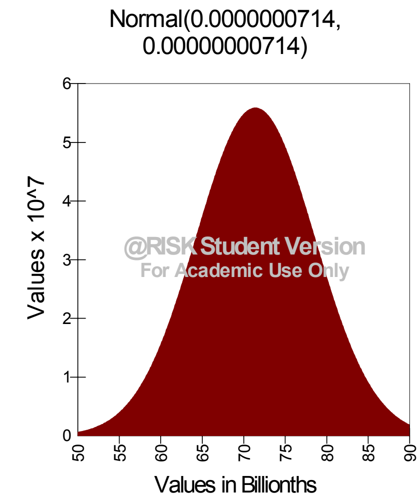
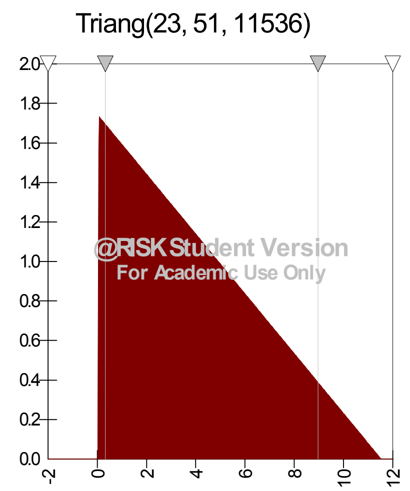
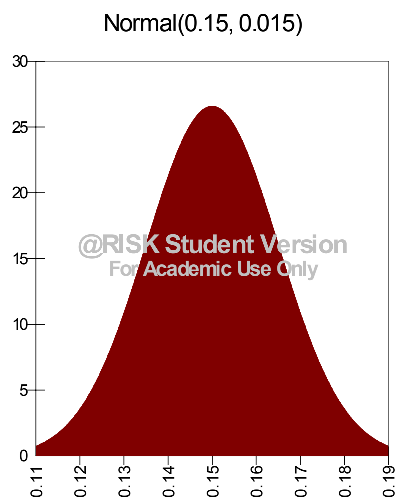
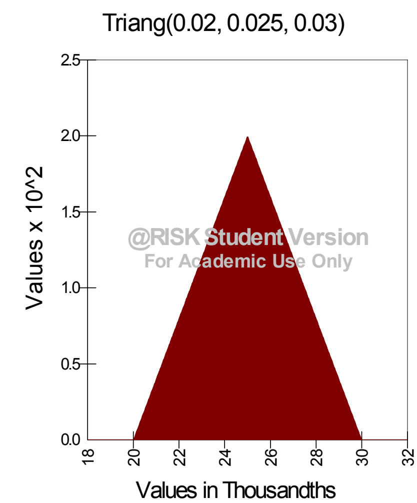
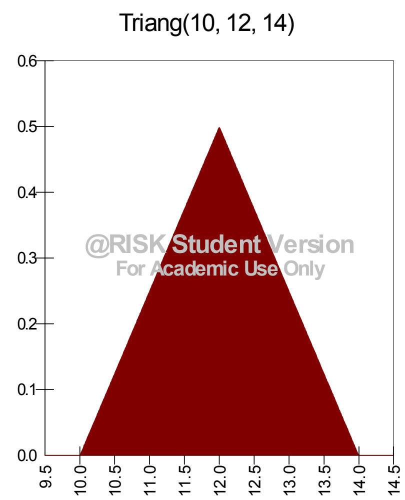
Table C – 7: CBA results for closed parking buildings: sprinkler extension not available & private – Scenario 3

Annual Usage Ratio (R)	**Total floor area of parking building (A, m^2)**									
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000
0	-0.4	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
500	-0.4	-0.1	0.0	0.1	0.2	0.2	0.2	0.2	0.3	0.3
1000	-0.4	0.1	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.6
1500	-0.4	0.2	0.5	0.7	0.8	0.8	0.9	0.9	1.0	1.0
2000	-0.4	0.4	0.7	0.9	1.1	1.1	1.2	1.3	1.3	1.3
2500	-0.4	0.5	1.0	1.2	1.3	1.5	1.5	1.6	1.6	1.7
3000	-0.4	0.7	1.2	1.5	1.6	1.8	1.9	1.9	2.0	2.0
3500	-0.4	0.9	1.4	1.7	1.9	2.1	2.2	2.3	2.3	2.4
4000	-0.4	1.0	1.6	2.0	2.2	2.4	2.5	2.6	2.7	2.7
4500	-0.4	1.2	1.9	2.3	2.5	2.7	2.8	2.9	3.0	3.1
5000	-0.4	1.3	2.1	2.5	2.8	3.0	3.2	3.3	3.4	3.4
5500	-0.4	1.5	2.3	2.8	3.1	3.3	3.5	3.6	3.7	3.8
6000	-0.4	1.6	2.5	3.1	3.4	3.6	3.8	3.9	4.0	4.1
Annual Usage Ratio (R)	**Total floor area of parking building (A, m^2)**									
	10000	20000	30000	40000	50000					
0	-0.1	0.0	0.0	0.0	0.0					
500	0.3	0.3	0.4	0.4	0.4					
1000	0.6	0.7	0.7	0.8	0.8					
1500	1.0	1.1	1.1	1.2	1.2					
2000	1.4	1.5	1.5	1.6	1.6					
2500	1.7	1.9	1.9	2.0	2.0					
3000	2.1	2.3	2.3	2.4	2.4					
3500	2.4	2.6	2.7	2.8	2.8					
4000	2.8	3.0	3.1	3.2	3.2					
4500	3.1	3.4	3.5	3.6	3.6					
5000	3.5	3.8	3.9	4.0	4.0					
5500	3.8	4.2	4.3	4.4	4.4					
6000	4.2	4.6	4.7	4.8	4.8					

Table C – 8: CBA results for closed parking buildings: sprinkler extension not available & public – Scenario 4

Annual Usage Ratio (R)	Total floor area of parking building (A, m^2)									
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000
0	-0.4	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
500	-0.4	-0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
1000	-0.4	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.4
1500	-0.4	0.1	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7
2000	-0.4	0.2	0.5	0.6	0.7	0.8	0.8	0.9	0.9	0.9
2500	-0.4	0.3	0.6	0.8	0.9	1.0	1.0	1.1	1.1	1.2
3000	-0.4	0.4	0.8	1.0	1.1	1.2	1.3	1.3	1.4	1.4
3500	-0.4	0.5	0.9	1.2	1.3	1.4	1.5	1.6	1.6	1.6
4000	-0.4	0.6	1.1	1.4	1.5	1.6	1.7	1.8	1.8	1.9
4500	-0.4	0.7	1.2	1.5	1.7	1.9	2.0	2.0	2.1	2.1
5000	-0.4	0.9	1.4	1.7	1.9	2.1	2.2	2.3	2.3	2.4
5500	-0.4	1.0	1.6	1.9	2.1	2.3	2.4	2.5	2.6	2.6
6000	-0.4	1.1	1.7	2.1	2.3	2.5	2.6	2.7	2.8	2.9
Annual Usage Ratio (R)	Total floor area of parking building (A, m^2)									
	10000	20000	30000	40000	50000					
0	-0.1	0.0	0.0	0.0	0.0					
500	0.2	0.2	0.2	0.2	0.2					
1000	0.4	0.5	0.5	0.5	0.5					
1500	0.7	0.8	0.8	0.8	0.8					
2000	0.9	1.0	1.1	1.1	1.1					
2500	1.2	1.3	1.3	1.4	1.4					
3000	1.4	1.6	1.6	1.6	1.7					
3500	1.7	1.8	1.9	1.9	1.9					
4000	1.9	2.1	2.2	2.2	2.2					
4500	2.2	2.4	2.4	2.5	2.5					
5000	2.4	2.6	2.7	2.8	2.8					
5500	2.7	2.9	3.0	3.0	3.1					
6000	2.9	3.2	3.3	3.3	3.4					

Table C – 9: Probability distribution for each input in @RISK for both scenarios

For Scenario 2 (sprinkler extension available) and Scenario 4 (sprinkler extension not available)	
 ∑ (f × n) for non-sprinklered	 f_s for sprinklered
 Unit fire damage – D	 Reduction percentage – p
 Sprinkler marginal maintenance – M_m	 Sprinkler marginal initial – I_m

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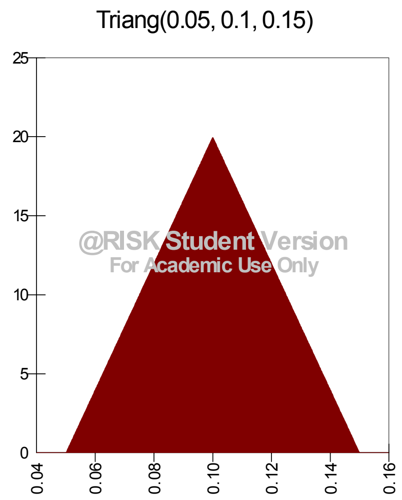
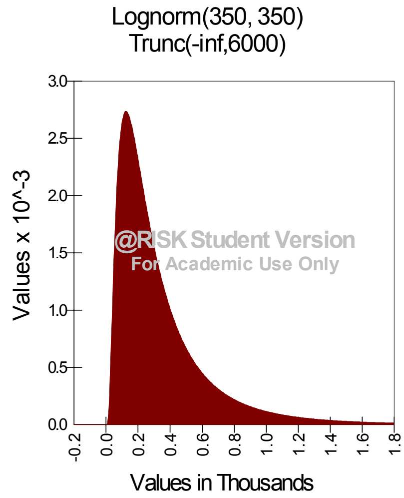
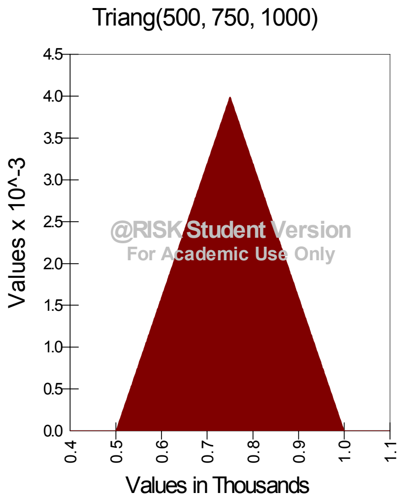


Discount rate – i

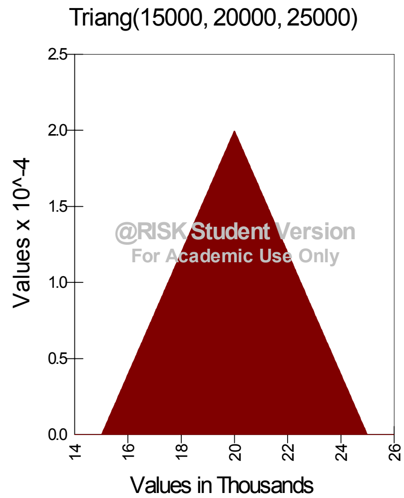


Annual usage ratio – R

For Scenario 4 (sprinkler extension not available)

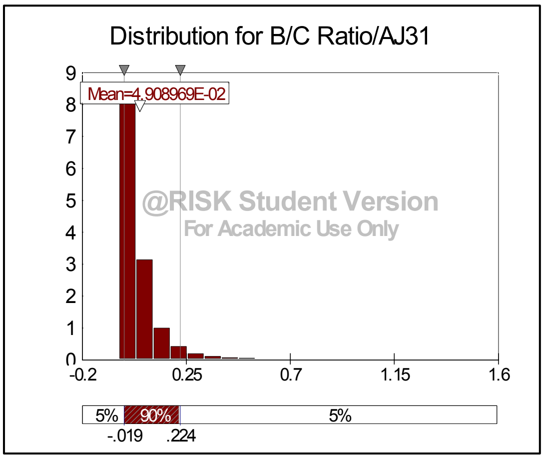


Sprinkler fixed maintenance – M_F

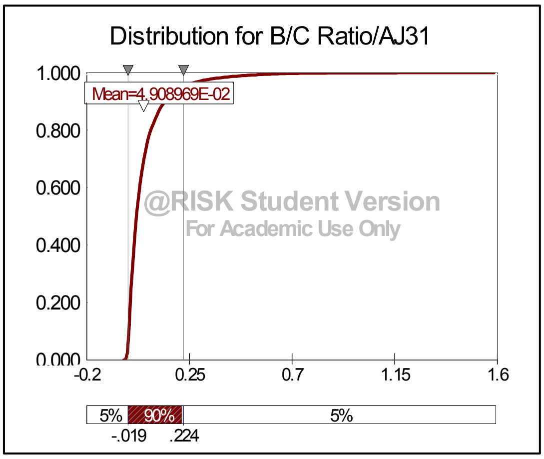


Sprinkler fixed initial – I_F

Table C – 10: The output results from @RISK for sprinkler extension available (Scenario 2)



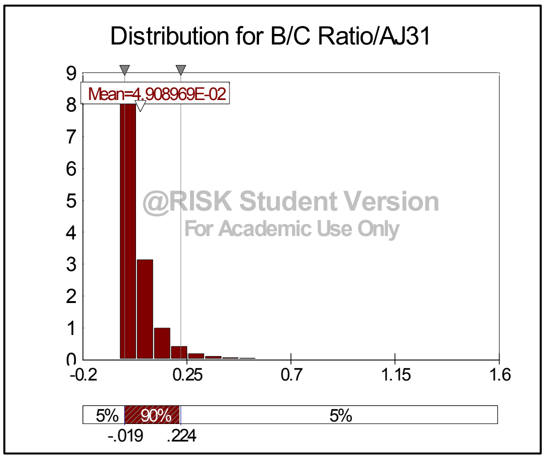
Probability Distribution



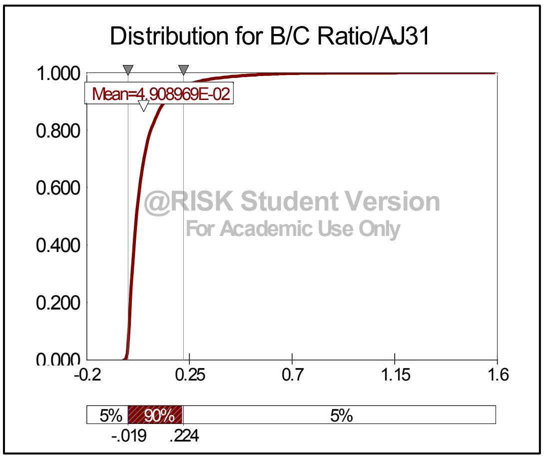
Cumulative Probability Distribution

Summary Statistics of Cost-Benefit Ratio			
Statistic	Value	Percentile	Value
Minimum	-0.04	5%	-0.019
Maximum	1.59	10%	-0.015
Mean	0.049	15%	-0.012
Std Dev	0.10	20%	-0.009
Variance	0.0099	25%	-0.006
Skewness	4.0883	30%	-0.002
Kurtosis	30.0890	35%	0.002
Median	0.02	40%	0.007
Mode	-0.01	45%	0.011
Left X	-0.02	50%	0.017
Left P	5%	55%	0.024
Right X	0.22	60%	0.031
Right P	95%	65%	0.040
Diff X	0.24	70%	0.050
Diff P	90%	75%	0.063
#Errors	-	80%	0.081
Filter Min	-	85%	0.105
Filter Max	-	90%	0.142
#Filtered	-	95%	0.224

Table C – 11: The output results from @RISK for sprinkler extension not available (Scenario 4)



Probability Distribution



Cumulative Probability Distribution

Summary Statistics of Cost-Benefit Ratio

Statistic	Value	Percentile	Value
Minimum	-0.08	5%	-0.04
Maximum	3.07	10%	-0.04
Mean	0.026	15%	-0.03
Std Dev	0.10	20%	-0.03
Variance	0.0096	25%	-0.02
Skewness	5.3895	30%	-0.02
Kurtosis	65.3303	35%	-0.02
Median	0.00	40%	-0.01
Mode	-0.05	45%	-0.01
Left X	-0.04	50%	0.00
Left P	5%	55%	0.00
Right X	0.19	60%	0.01
Right P	95%	65%	0.02
Diff X	0.23	70%	0.03
Diff P	90%	75%	0.04
#Errors	-	80%	0.06
Filter Min	-	85%	0.08
Filter Max	-	90%	0.12
#Filtered	-	95%	0.19

Table C – 12: Sensitivity analysis – sprinkler extension available (Scenario 2)

Rank	Name	Regression Coefficient
#1	Annual usage ratio – R	0.694
#2	Unit fire damage – D	0.489
#3	Discount rate – i	-0.092
#4	Non-sprinklered – $\sum f \times n$	0.084
#5	Marginal initial– I_m	-0.034
#6	Marginal maintenance – M_m	-0.018
#7	Reduction percentage – p	-0.016
#8	Sprinklered – f_s	-0.014

Table C – 13: Sensitivity analysis – sprinkler extension not available (Scenario 4)

Rank	Name	Regression Coefficient
#1	Annual usage ratio – R	0.681
#2	Unit fire damage – D	0.481
#3	Non-sprinklered – $\sum f \times n$	0.083
#4	Discount rate – i	-0.056
#5	Fixed maintenance – M_F	-0.025
#6	Marginal maintenance – M_m	-0.018
#7	Marginal initial – I_m	-0.017
#8	Sprinklered – f_s	-0.012
#9	Reduction percentage – p	-0.011
#10	Fixed initial – I_F	0.000